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Evaluation of the sustainability index of geotechnical infrastructure for the stability of rural roads: case study of Subachoque-Tabio-Chía road, Cundinamarca, Colombia.

Evaluación del índice de sostenibilidad de obras geotécnicas para la estabilidad de vías rurales: caso de estudio carretera Subachoque-Tabio-Chía, Cundinamarca, Colombia.

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ABSTRACT: The multi-criteria evaluation of the sustainability aspects of the construction, operation, and management of the latest road infrastructure in the department of Cundinamarca, Colombia, focuses on a case study of a tertiary road linking the municipalities of Chía, Tabio, and Subachoque. This research is a response to the growing demand for housing around the country's capital, which requires a functional, efficient, and sustainable road infrastructure in environmental, social, and economic terms. The main objective is to analyze how sustainability principles are integrated into the different geotechnical structures of the road infrastructure in the region. The methodology used combines economic, social, and environmental analysis to determine the sustainability index of the 56CN20-1 route. Strategies such as measuring the sustainability index are aimed at reducing environmental impact, optimizing the use of natural resources, and fostering community participation, which would also complement the resilience index to prevent the impact of extreme events on geotechnical works. The results obtained highlight the importance of evaluating the sustainability index as a conclusive tool for designing strategies and making decisions in risk management projects.

KEYWORDS: Sustainability index, geotechnical works, rural roads

1 INTRODUCTION

The latest official census shows that close to 10 million people live in Bogotá and Cundinamarca, with 71% distributed in Bogotá and 29% in Cundinamarca (DANE, 2019d). This distribution highlights the need for transportation infrastructure connecting rural and urban areas, especially between Bogotá and municipalities such as Chía, Tabio and Subachoque, which are undergoing socioeconomic expansion. Industrialization and housing growth in these areas drive the demand for road infrastructure to improve connectivity with the capital(Alcaldía de Bogotá, 2022).

In tropical regions such as Colombia, population growth and road infrastructure affect land use, reducing forest areas and leading to displacement, biodiversity loss and accelerated climate change (Gallice et al., 2019; Laurance et al., 2009). These regions, with their particular biodiversity and climate, face threats such as extreme weather events and land degradation (Ortega et al., 2001).

Since the adoption of the 2030 Agenda, the 193 UN member states have worked on economic, social and environmental sustainability through 17 Sustainable Development Goals (SDGs) (United Nations, 2023). SDG 9 highlights the importance of developing sustainable, resilient and accessible infrastructure, interconnecting with other SDGs such as 11 (Sustainable Cities and Communities), 7 (Affordable and Clean Energy) and 13 (Climate Action) (CEPAL, 2019, 2021a, 2021b, 2023).

Assessing the sustainability and resilience of urban and rural infrastructure is crucial for long-term community safety and well-being, using modern geotechnical methods that address challenges in systems vulnerable to disruptive events (Reddy et al., 2024). Geotechnics helps predict the performance of infrastructures in the face of environmental or anthropogenic hazards (Ausilio & Zimmaro, 2017), highlighting that sustainable structures exhibit high adaptability and resilience, crucial for stability and safety (Calvente, 2007; Lu et al., 2020).

1.1 Legal and regulatory framework for sustainability assessment in Colombia

In Colombia, the promotion of sustainability has become a key priority, reflected in a series of existing laws and regulations that seek to ensure a balance between economic, social and environmental development. Sustainability legislation in Colombia started with Law 99 of 1993, known as the General Environmental Law (CONGRESO DE COLOMBIA, 1993) until the implementation of the National Policy on Climate Change (Ministerio de Ambiente y Desarrollo Sostenible, 2017), the country has made significant progress in creating a robust legal framework to address environmental challenges and promote sustainable practices.

Table 1. Resumen marco normativo de la legislación Colombia para la sostenibilidad.

Tipo	Resolución	Alcance
Law	99 de 1993	Creation of the Ministry of the Environment and reorganization of the Colombian environmental sector. Requirement for environmental impact assessments for road infrastructure projects.
	388 de 1997	Inclusion of sustainability in territorial development planning and management, including road infrastructure.
	1753 de 2015	Amendment of Law 99 of 1993 and new provisions in environmental matters. Strengthening of the National Environmental System and inclusion of new instruments for environmental management, including sustainability assessment.
Decree	2820 de 2010	Establishment of requirements for environmental studies, including sustainability assessment.
	1076 de 2015	Regulation of environmental impact assessment and criteria for sustainability assessment in road infrastructure projects.
Resolution	0909 de 2008	Adoption of the Manual for the Application of Environmental Assessment for Road Infrastructure Projects. Technical guidelines for sustainability assessment.
	1755 de 2015	Adoption of General Guidelines for Environmental Impact Assessment and Formulation of Environmental Management Plans. Criteria for sustainability assessment in road infrastructure projects.

Methodological Guide	Methodological framework for sustainability as sessment in road infrastructure projects.

This legislation not only establishes the principles and rules for the management of the environment and natural resources, but also promotes sustainable territorial development, integrated water resource management, sustainable production and consumption, among other key aspects to guarantee a prosperous and equitable future for present and future generations.

2 DESCRIPCIÓN DE LA ZONA DE ESTUDIO.

2.1 Descripción demográfica

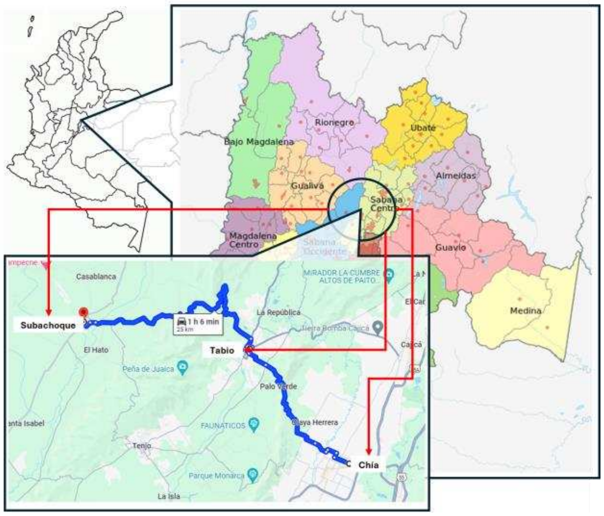


Figure 1. Location of the municipalities Chía – Tabio – Subachoque. Source: Adapted from (Google Maps, 2024)

The following is an overview of the demographic description of the study area within the framework of the Sustainability Index. This analysis provides a comprehensive overview of the population factors that influence the socio-economic and environmental dynamics of the municipalities of Subachoque, Tabio and Chía in the region, thus providing a solid basis for understanding the challenges and opportunities for sustainable development in this region.

2.1.1 *Chía*

Chía, located in the south of Cundinamarca, Colombia, has a projected population of 160,435 inhabitants by 2023, with a density of 4,444 inhabitants per km² and an annual growth rate of 2.59% (DANE, 2019c). 67.2% of dwellings are owned and 29.3% rented, but 10.2% face overcrowding. Chía's economy is diverse, with industry, commerce and services, with an unemployment rate of 8.2% in 2020. Companies such as Alpina, Bavaria, Terpel and Colsubsidio drive the local economy (Alcaldía Municipal de Chía, 2024). Mobility is based on car, bus and bicycle, with an average commuting time of 30 minutes. Chía has basic public services and a variety of educational institutions, health centres, parks and green areas that improve the quality of life (Alcaldía Municipal de Chía, 2024).

2.1.2 *Tabio*

Tabio, in the centre of Cundinamarca, has an area of 74.5 km² and an average altitude of 2,569 metres. It is projected to have a population of 31,145 inhabitants by 2023, with a density of 417 inhabitants per km² and an annual growth rate of 1.58% (Alcaldía Municipal de Tabio, 2024). 70.1% of dwellings are owned, 25.4% are rented, and 8.3% are in overcrowded conditions (DANE, 2019b). The economy is based on the primary and tourism sectors, with agriculture and livestock as traditional activities, and tourism growing. The unemployment rate in 2020 was 5.2%. Companies such as Cementos Argos, Alpina and Colanta boost the local economy (Alcaldía Municipal de Tabio, 2024). In terms of mobility, the main means of transport are cars, buses and bicycles, with an average commuting time of 25 minutes. The municipality has basic public services and a network of social facilities that includes educational institutions, health centres, parks and green areas (Alcaldía Municipal de Tabio, 2024).

2.1.3 *Subachoque*

Subachoque, located in the centre of Cundinamarca, has an area of 29.4 km² and an average altitude of 2,640 metres. Its average annual temperature is 14°C (Alcaldía Municipal de Subachoque, 2024). Located 45 kilometres from Bogotá, Subachoque projects a population of 17,544 inhabitants by 2023, with a population density of 593 inhabitants per km² (DANE, 2019a). The economy is based on the primary and industrial sectors, with a low unemployment rate of 4.9% in 2020. Companies such as Postobón, Bavaria and Alpina drive local economic development. The municipality offers basic services of drinking water, sewerage, electricity and natural gas, as well as a solid network of social facilities with educational institutions, health centres, parks and green areas (Alcaldía Municipal de Tabio, 2024).

2.2 Description of road infrastructure

Cundinamarca has 1615 roads connecting its municipalities and interdepartmental transit (Gobernación de Cundinamarca, 2023). The Chía-Tabio-Subachoque road network is key for transport and economic development, facilitating the mobility and exchange of people, goods and agricultural products (Chisco, 2015). The Chía-Tabio-Subachoque road, 25 km long and 9.3 m wide on average, crosses mountainous and agricultural terrain, facing geotechnical challenges such as steep slopes, erosion and landslides (Ministerio De Transporte, 2017). Resolution No. 1530 of 2017 classifies the Subachoque-Tabio-Chía road (code 56CN20-1) as second order due to its intermunicipal function (Resolution 1530 of 2017, 2017).

2.2.1 *Road inventory of the municipality of Chía*

The municipality of Chía has an extensive road network which is divided into two main areas: urban and rural. Each of these zones has different road characteristics and needs. The road network of the municipality of Chía is shown in Figure 4, where the blue lines represent the trunk or national roads, and the grey lines represent the collector roads.

The urban area has a basic road infrastructure, including paved roads, road signs, street lighting and traffic lights. However, this infrastructure is deficient in some sectors, which causes deficiencies in mobility, especially at peak hours, and difficulties for freight traffic due to the state of some roads.

As shown in Table 2, the main road network of the municipality of Chia has 10 roads categorised by MinTransport, which total approximately 45 km, currently 5 of the 10 reported roads are under construction or the update of their categorisation and characteristics has not been carried out.

Forty percent of the roads are classified as collector roads, 10% correspond to trunk roads, 20% correspond to national roads and the remaining 30% correspond to municipal roads. The national roads lead to the region of Ubaté and Tunja, while the municipal roads connect to Bogotá and El Canelón.

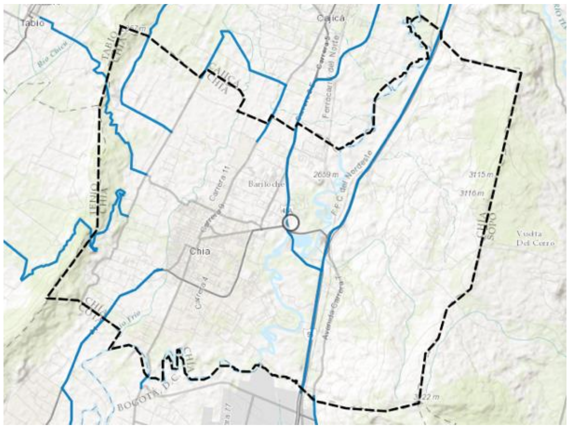


Figure 2. Distribution of road infrastructure in the municipality of Chía. Source: (Gobernación de Cundinamarca, 2023)

Table 2. Road categorization of the municipality of Chía

Route	*Road Class*	*Destination*	*Length (km)*
Tiquiza - Vereda Fagua	Collector	Vereda Fagua	3,9
Chía - Cota	Trunk	Cota	8
Chía - Cajicá	Collector	Cajicá	10,3
Bogotá - Ubaté	National	Ubaté	EC
Límite de Chía y Cajicá - El Canelón	Municipal	El Canelón	EC
Tenjo - Cruce de Tenjo	Collector	Cruce de Tenjo	15,4
Chía - Cruce de Tenjo – Tabio	Collector	Tabio	8
Bogotá - La Caro - Tunja	National	Tunja	EC
Avenida Carrera 7	Municipal	Bogotá	EC

Fuente: (Gobernación de Cundinamarca, 2023)

2.2.2 *Road inventory of the municipality of Tabio*

The road infrastructure of the municipality of Tabio, Cundinamarca, is made up of a network of roads that connect the municipality with neighbouring towns and with the city of Bogotá. The road network is made up of 70 kilometres of roads, distributed into 35.4 kilometres of departmental roads and 34.6 kilometres of municipal roads. Of these roads, 60% are in good condition, 30% are in fair condition and 10% are in poor condition.

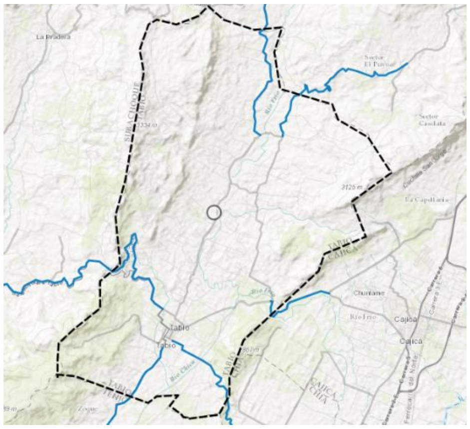


Figure 3. Distribution of road infrastructure in the municipality of Tabio. Source: (Gobernación de Cundinamarca, 2023)

The municipality has an urban road network that is in fair condition. Most of the streets are paved, but some are in poor condition and require maintenance. On the other hand, most of the rural road network is unpaved and in poor condition, which makes access to the rural areas of the municipality difficult.

Table 3. Road categorization of the municipality of Tabio.

Route	*Road Class*	*Destination*	*Length (km)*
Tabio - Cajicá	Collector	Cajicá	10
Chía - Cruce de Tenjo - Tabio	Collector	Tabio	8
Cruce de Tabio - San Jorge	Collector	San Jorge	8,4
La Recebera - Cruce de Tabio	Collector	Cruce de Tabio	8,2
Tabio - Subachoque	Trunk	Subachoque	9,8
Subachoque - La Pradera - Alto del Águila	Trunk	Alto del Águila	18,6
Tenjo - Tabio	Trunk	Tabio	7

Fuente: (Gobernación de Cundinamarca, 2023)

Table 3 shows the categorisation of the road network of the municipality, where in the last road inventory of Cundinamarca 8 departmental roads were recognised, which lead to municipalities such as Cajicá, San Jorge, Subachoque. The roads allow the interconnection of the department and municipalities such as Chía, Zipaquirá, among others.

2.2.3 *Road inventory of the municipality of Subachoque*

Due to the urban expansion in the municipality of Subachoque, the development plans of the region have included a higher percentage of investment with respect to other periods for the improvement of mobility through maintenance and repairs of the existing road network, as well as projects for the expansion and construction of new municipal and departmental roads that allow the interconnection of the municipality with the surrounding municipalities.

Figure 7 shows a representation of the distribution of the 113.73 kilometres of roads in the municipality of Subachoque, where the blue lines represent the departmental connection roads, which correspond to approximately 25%, and the municipal connection roads correspond to the grey lines and represent 75% of the road network of the municipality.

The roads with the most traffic in the municipality are the roads leading to Puntepiedra, El Rosal, El Tablazo and Guamal. Table 4 shows the details of the roads reported by the Gobernación de Cundinamarca for the road inventory of the municipality (Gobernación de Cundinamarca, 2023).

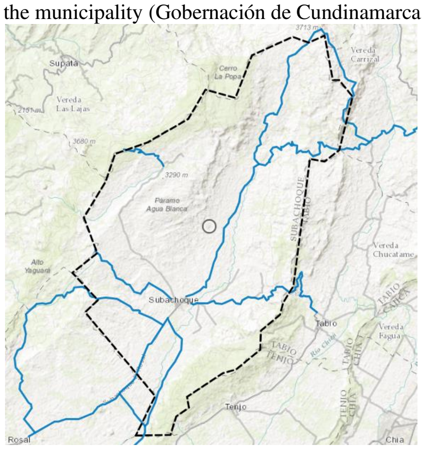


Figure 4. Distribución de la infraestructura vial del municipio de Subachoque. Fuente: (Gobernación de Cundinamarca, 2023)

Table 4. Road categorization of the municipality of Subachoque.

Route	*Road Class*	*Destination*	*Length (km)*
San Antonio - La Recebera	Collector	La Recebera	6,3
Subachoque - La Hondura - El Rosal	Collector	El Rosal	18,13
La Cuesta - La Porquera	Collector	La Porquera	2,6
La Pradera / San Antonio - Guamal	Collector	Guamal	9,3
Tabio - Subachoque	Trunk	Subachoque	9,8
Subachoque - La Pradera - Alto del Águila	Trunk	Alto del Águila	18,6
Subachoque - El Rosal	Collector	El Rosal	14,4
Subachoque - Puentepiedra	Collector	Puentepiedra	14
Subachoque - Paramillo - El Tablazo	Collector	El Tablazo	15

Fuente: (Gobernación de Cundinamarca, 2023)

2.3 *Description of geotechnical structures*

The characterization and classification of the geotechnical structures and the elements that compose them, such as drainage, signaling, services, among others, were evaluated based on the methodology proposed by (Pineda et al., 2024). This methodology suggests performing a visual inspection at the study site and reviewing the state of service of each of the elements. Although it was initially developed to estimate the resilience index, its application is equally effective for describing geotechnical works in the study of the sustainability index. This is because it provides a comprehensive assessment of the functionality and maintenance required for each element, ensuring that they can not only withstand and recover from disruptive events, but also operate, recover and maintain themselves sustainably over the long term.

Route 56CN20-1 leading from the municipality of Chia to the municipality of Subachoque begins its route from the exit of the municipality of Chia with a third order road, with a roadway width of approximately 6 m, is a material road, unpaved except for some areas of reparcheo that has pavement, but these areas do not exceed 100 m in length. Traffic on this road is limited to a maximum of one vehicle per direction. This section of the road is dominated by vegetation on the road without adequate vegetation clearance control, which can limit the constant flow of traffic in the area (see Figure 5).

Safety on the road can be compromised in sections where there is evidence of sedimentary rock cuttings, as there is no evidence of any protection system against falling material on these sections of the road (see figure 6). In addition, most of the road signage systems are covered by vegetation, preventing the correct visualisation of these by people passing through this sector (see figure 7).

Figure 5. State of the Chía - Tabio road. Source: Adapted from (Google Maps, 2024).

Figure 6. Unprotected rock cuts on the Chía - Tabio road. Source: Adapted from (Google Maps, 2024).

The drainage systems have the basic maintenance, allowing the water to pass through in a channelled manner, without affecting the structure of the road or affecting mobility in the area due to possible flooding (see figure 8). In the urban areas through which the road passes, there is evidence of the presence of side boundaries on the roads, lighting, signage and the road has a pavement in good condition (see figure 9).

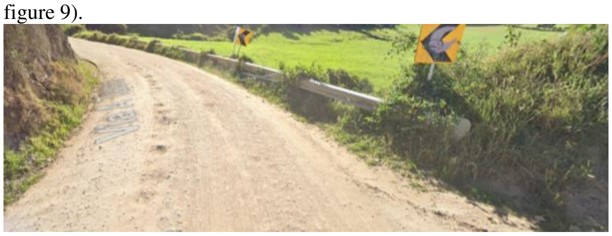


Figure 7. State of road signage on the Chía - Tabio road. Source: Adapted from (Google Maps, 2024).

The road section leading from Tabio to Subachoque is considered a second order road, with a roadway width of approximately 7.5 m, which allows the circulation of one vehicle per section of the roadway. Unlike the road leading from the municipality of Chía to Tabio, this road is mostly paved, but presents considerable pathologies, which affect the correct mobility in the area (See figure 10).

Figure 8. Drainage system of the Chía - Tabio road. Source: Adapted from (Google Maps, 2024).

Figure 9. State of roads in urban areas between Tabio and Subachoque. Source: Adapted from (Google Maps, 2024).

Figure 10. State of roads from Tabio to Subachoque. Source: Adapted from (Google Maps, 2024).

The drainage systems on this road are not well maintained, as most of the drainage systems inspected are covered with vegetation or solid waste (see figure 11).

In this section of the road, it is also evident that the road signs are in very poor condition or lack maintenance, as most of them are covered by thick vegetation, putting traffic through these areas at risk.

Figure 11. Sistema de drenaje de la vía Tabio – Subachoque. Fuente: Adaptado de (Google Maps, 2024)

Figure 12. Estado de la señalización de la vía Tabio – Subachoque. Fuente: Adaptado de (Google Maps, 2024)

The road section from Tabio to Subachoque is shaped differently depending on the terrain. In the lower mountainous areas, embankments are used to form the road. In the higher mountainous areas, it is assumed that the road was constructed using cuttings and slope stabilization techniques.

Geotechnical works such as slopes, embankments, retaining walls and road drainage are closely related to the sustainability index because of their influence on natural resource consumption, greenhouse gas emissions during road construction and operation, environmental and social impacts, and their ability to withstand the effects of climate change and natural hazards. The adoption of sustainable construction practices, efficient resource management, mitigation of environmental and social impacts, and design for resilience are essential to improve the sustainability index of these geotechnical works (Reddy et al., 2024).

2.3 Description of sustainability plans

In the last development plan presented for the department of Cundinamarca, which was called "governing more than a plan", some sustainability strategies are presented with the purpose of turning the department into a prosperous, equitable and sustainable territory for present and future generations. The aim is to achieve this purpose through strategies such as: presenting projects focused on the conservation and restoration of ecosystems, promotion of sustainable agricultural practices and integrated water resource management, promotion of activities that help reduce greenhouse gas emissions, adaptation to climate change, and risk management, and last but not least, it is proposed to invest in training for large and small producers to implement circular economy strategies that allow them to reduce waste, recycling and reuse of materials (Gobernación de Cundinamarca, 2024).

The sustainable development plans of the municipalities of Chía, Tabio and Subachoque focus on three key components: environmental, social and economic. In Chía, priority is given to the protection of the Reserva Forestal de la Cuenca Alta Río Bogotá, reforestation, the use of sustainable transport, improving education and health, and promoting entrepreneurship and infrastructure. Tabio focuses on community participation and social investment, promoting sustainable tourism, environmental education and the circular economy, along with mechanisms for citizen participation. Subachoque seeks social and environmental well-being through environmental protection, circular economy, quality education and social inclusion, with an emphasis on improving road infrastructure to promote mobility, trade and tourism.

3 METHODOLOGY

3.1 *State of the Art*

Road infrastructure in Colombia faces challenges due to relief and climatic changes. Geotechnical works, such as retaining walls and drainage, are essential for the stability and safety of roads. It is crucial to design and build them in a sustainable way, considering environmental, social and economic aspects.

The sustainability index is a tool to assess the impact of a work or project, including the use of sustainable materials, minimisation of environmental impact, involvement of the local community and economic viability.

Sustainability studies in geotechnical engineering focus on the life cycle of materials and construction processes to quantify their environmental and socio-economic impacts. The sustainability index considers the environmental measurement (environmental impacts, use of natural resources, emission of pollutants and waste generation), the economic aspect (construction, maintenance and operation costs, impact on the budget of the territory or the community) and the social consequences of the project (impact on people's health and safety, social welfare, equity and community participation).

Sustainability studies in geotechnical engineering focus on assessing the life cycle of materials and construction processes to quantify their environmental and socio-economic impacts. The calculation of the sustainability index covers dimensions such as environmental measurement, which includes environmental impacts, use of natural resources, emission of pollutants and waste generation; the economic aspect, which considers construction, maintenance and operation costs, as well as their impact on the budget of the territory or the community; and the social consequences of the project, such as its impact on people's health and safety, social welfare, equity and community participation. Given the importance of these aspects, multi-criteria assessment methodologies are proposed to analyse the use of resources, allowing for a comprehensive assessment of system sustainability and more informed decision-making in geotechnical engineering (Das et al., 2018).

The development of a sustainability assessment tool specifically for dam projects, called the Geotechnical Sustainability Assessment Tool (Geo-SAT), uses technical indicators to assess the sustainability of such projects. However, the research points out that the indicators initially used in Geo-SAT are asymmetric because they are assigned equal weights and do not take into account the variability of their importance in different projects and life cycle stages. This limitation in the tool was solved by means of scale normalisation using Multiple Criteria Decision Analysis (MCDA) and Multiple Attribute Value Theory (MAVT), whose inputs for the analysis were obtained through surveys and interviews with relevant experts in the field, who provided their opinion on the importance of the indicators at all stages of the project life cycle (Batool et al., 2023).

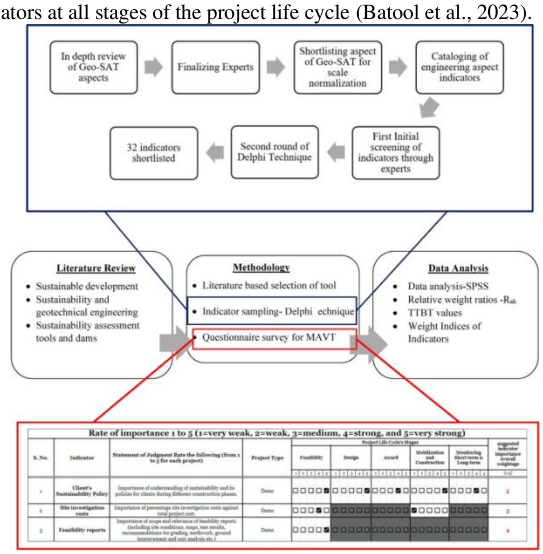


Figure 13. Current research framework for Geo-SAT scale standardization. Source: (Batool et al., 2023)

Then, importance weights and relative weights of the indicators were calculated using MAVT based on the experts' responses. In the end the research concludes that the most critical indicators for the assessment of the sustainability of dams were identified, such as quality control during construction, waste of construction materials and feasibility reports. These indicators were assigned specific maximum weights (Batool et al., 2023).

Based on the reference literature for the development of this research, it is proposed that the indicators for the sustainability index in geotechnical engineering encompass environmental, economic and reliability aspects, thus ensuring that optimal designs are feasible and sustainable in the long term. To measure the environmental impact, the amount of natural resources used, carbon emissions generated and energy consumption during the construction and operation of geotechnical projects are considered. In economic terms, the costs associated with the design, construction and maintenance of such projects are analysed. Regarding the social component, it is crucial to assess the reliability of the project in terms of its ability to meet the standards of the social dynamics of the territory where it is located, including the probability of failure as a relevant factor in the sustainability index (Basu & Lee, 2022).

The Quantitative Assessment of Life Cycle Sustainability (QUALICS) is based on a method that divides sustainability into three levels. The environmental level assesses the impact of a project or activity through indicators such as carbon dioxide emissions, water consumption and deforestation. The social level considers specific indicators to measure social impact, such as unemployment rate, income level and access to education. Finally, the economic level analyses the economic viability of the project through indicators such as total cost, income generated and payback period. The sustainability index is a quantitative measure calculated by taking the average of the three sustainability scores: environmental, social and economic. The weights for environmental, social and economic sustainability are numbers that reflect the relative importance of each of these factors in determining overall sustainability (Basu & Lee, 2022).

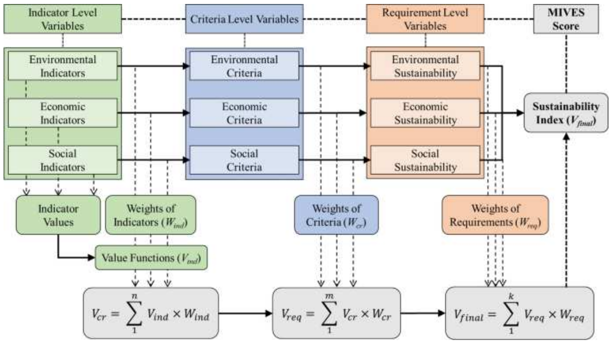


Figure 14. Methodology for calculating the sustainability index using the MIVES method. Source: (Basu & Lee, 2022)

In general, methodologies for estimating the sustainability index for road infrastructure projects involve the selection and weighting of relevant criteria, consideration of comprehensive theoretical models, evaluation of the impact of additional criteria, and the use of assessment scales to measure the influence of each component on the overall sustainability of the project (Ametepey et al., 2023).

3.2 *Key Performance Indicators (KPIs) of Sustainability*

Sustainability Key Performance Indicators (KPIs) are metrics used to measure the environmental, social, and economic performance of a project (Quiroga Martínez, 2009). Assessing sustainability in projects is a complex process that requires consideration of multiple indicators and perspectives. (Shen et al., 2011) conducted a study involving various experts to rate the importance of each indicator for estimating the sustainability index. Their approach is considered valuable for understanding diverse priorities and perceptions regarding the sustainability of road infrastructure projects.

The selection of sustainability indicators for this research was guided by the importance levels identified by (Shen et al., 2011). This scale provided a detailed view of the priorities among different expert groups, revealing significant discrepancies in the perceived relevance of each indicator. Each indicator must be evaluated on a five-point scale, where 5 means excellent, 4 good, 3 moderate, 2 acceptable, and 1 poor.

The road connecting the municipality of Chía to Subachoque is classified as a second-order road. Therefore, the KPIs used in this research to evaluate sustainability will encompass those measuring the impact of road operation on the environment, local community, and economy.

3.2.1 *Environmental KPIs for Sustainability*

Environmental indicators are estimated through actions that reflect a comprehensive approach to environmental sustainability in the planning, design, and execution of infrastructure projects (Ametepey et al., 2023).

Techniques such as life cycle assessment are used during both the construction and operation phases of road infrastructure to measure the environmental impact of project stages and materials used (Suprayoga et al., 2020).

Table 5 presents the environmental indicators evaluated for the operational phase of the road connecting the municipalities of Chía and Subachoque, based on official reports and statistics from the region. In 2012, the Regional Autonomous Corporation (CAR) invested over 80 billion Colombian pesos in environmental protection efforts, with 17% allocated to wastewater management, 10% to soil and groundwater protection, 29% to biodiversity conservation and landscape preservation, 42% to environmental management and administration, and the remaining 1% to other environmental protection measures (DANE, 2012).

The Institute of Hydrology, Meteorology, and Environmental Studies (IDEAM) monitors soil quality in Cundinamarca department. This monitoring includes various parameters depending on intended land use (agriculture, urbanization, conservation, etc.), covering aspects like soil texture, nutrient content, pH, organic matter content, and presence of contaminants (IDEAM, 2017).

(IDEAM, 2017) reported an annual decrease of approximately 1.35% in the area covered by heterogeneous agricultural land (pastures and crops) in Cundinamarca municipalities, indicating reduced contamination in surface soil layers and lowering the risk of structural stability alterations. Physical changes such as erosion have affected around 80% of the total area, with approximately 5% classified as severely to very severely eroded, largely due to changes in river courses and rainfall patterns influenced by regional climate change impacts.

Chemical changes in the region, particularly related to soil salinity, have led to soil degradation and changes in land use. Electrical conductivity measurements have indicated that about 29% of Cundinamarca's territory exhibits mild to moderate salinity levels, while 5% shows severe to very severe salinity levels (IDEAM, 2017).

The Air Quality Index (AQI) is determined using monitoring stations that collect data on atmospheric pollutants such as particulate matter <2.5 microns (PM2.5), carbon dioxide (CO2), relative humidity (R.H.), and temperature. Historical measurements of these pollutants aid decision-makers and stakeholders in assessing overall air quality in a region.

Cundinamarca department has 12 air quality monitoring stations, with the nearest station to the study area (Chía - Tabio - Subachoque) located in Chía municipality. For this study assessing the sustainability of the road from Chía to Subachoque in terms of operation and maintenance, historical data series reported by (IQAir, 2024) for atmospheric pollutants are analyzed.

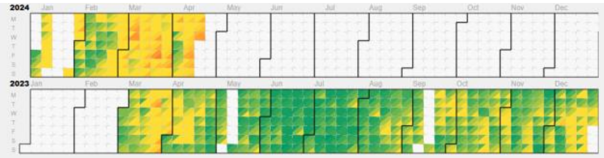


Figure 15. Contaminante $MP_{2.5}$. Fuente: Tomado de (IQAir, 2024).

The predominance of the green color in the PM2.5 report indicates that the particles present in the atmosphere are smaller than 2.5 microns, with the exception of the last quarter reported by the monitoring station. During this period, atmospheric particulate pollution is considered moderate, which coincides with the environmental impacts caused by the El Niño phenomenon in the region.

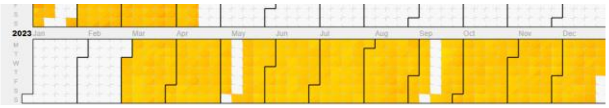


Figure 16. Régimen de temperatura. Fuente: Tomado de (IQAir, 2024).

The temperature index for the region reveals that, on average, temperatures range between 25°C and 27°C. During the first quarter of 2024, the average temperature was 25°C, with a maximum recorded temperature of 33°C. These data suggest that the region has experienced climate impacts primarily due to current environmental phenomena.

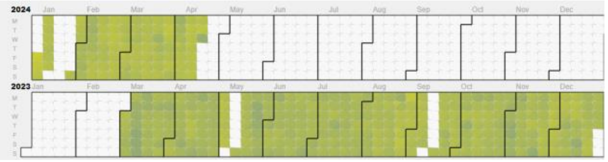


Figure 17. Humedad relativa. Fuente: Tomado de (IQAir, 2024).

Figure 17 reveals that the lowest relative humidity, between 28% and 29%, coincides with the lowest recorded temperatures, while the highest relative humidity, between 46% and 50%, was observed during periods of high temperatures. This suggests a correlation between temperature and relative humidity in the region.

Reports on air quality indicate that the environmental sustainability index of the road between Chía and Subachoque does not maintain a balanced state, especially during recess or holiday periods, when a significant impact is observed. Vehicular traffic on the route appears to be an influential factor in local air quality, exacerbated by recent climate changes and environmental phenomena.

Comprehensive assessment of water quality reveals it is influenced by natural factors such as volcanic activity and soil erosion, as well as human activities including domestic, industrial, and agricultural water use. Measurements indicate variability in water quality in the Chía, Subachoque, and Tabio watersheds, with areas showing slight improvements but consistently challenging maintenance.

Since 2015, CAR in partnership with the Global Biodiversity Information Facility (GBIF) has reported 5,535 occurrences in Cundinamarca department, where approximately 55% of occurrences are wildlife sightings and the remaining 45% are flora sightings. The year 2017 recorded the highest number of occurrences with 1,549 wildlife sightings and 523 flora sightings (GBIF & CAR, 2023).

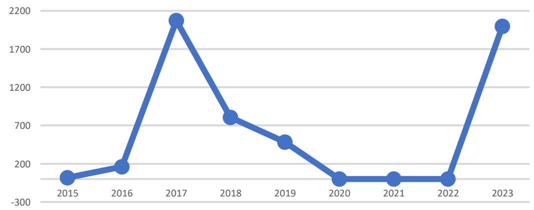


Figure 18. Biodiversity occurrences in the Department of Cundinamarca. Source: Taken from (GBIF & CAR, 2023)

According to the latest Greenhouse Gas Inventory report in Cundinamarca department, total emissions reached 15,614 kt CO2 eq, while absorption was -466.5 kt CO2 eq. The sector contributing the most to emissions is industry, accounting for 34% of the total, followed by transportation (15%), housing and sanitation (9%), mining and energy (8%), forest land management (4%), and agriculture (3%). Regarding GHG absorption, significant sectors in Cundinamarca include forest land management (65%), environmental resource management (35%), industry (2%), housing and sanitation (2%), transportation (1%), mining and energy (1%), and agriculture (0%) (IDEAM et al., 2022).

In Colombia, precise statistics on the natural resource consumption index are currently unavailable. However, departmental management plans and reports detail economic resources allocated to rehabilitating exploited resources to foster regional development. In the municipality of Subachoque, from 2020 to 2023, over 235 million pesos were allocated for acquiring, protecting, and restoring ecologically important properties through reforestation and maintenance actions. Additionally, environmental social responsibility programs were implemented to promote responsible identification and enjoyment of natural resources, fostering a sense of ownership and community responsibility in their care (Gobernación de Cundinamarca, 2020b, 2024).

In the municipality of Tabio, approximately 552 million pesos have been invested in the care and conservation of natural reserves in watershed basins, ensuring the supply of the minimum vital consumption for each municipality resident and for industrial operations. Similarly, in the municipality of Chía, over 12 billion pesos were invested in the comprehensive management of the Bogotá River basin, and in Subachoque, over 627 million pesos were invested for the same purpose (Gobernación de Cundinamarca, 2020b).

Table 5. Environmental indicators for the road from Chía to Subachoque

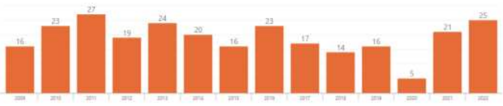
Indicator	*Description*	*Evaluation*
Soil Contamination	The evaluation of soil contamination indices considers the chemical and physical processes that cause the deterioration of the soil's surface layers	4
Air quality	Evaluation of atmospheric pollutants that modify air quality.	3
Water quality	Measurement of parameters such as turbidity, pH, electrical conductivity, presence of contaminants and organisms.	3
Biodiversity	Inventory of flora and fauna species present in the area of influence of the project to assess local biodiversity.	5
Greenhouse gas emissions	Quantification of CO2 and other gas emissions to assess their contribution to climate change.	4
Consumption of natural resources	Monitoring the consumption of water, energy, construction materials and other natural resources to promote the efficient use of resources.	4

3.2.2 *KPIs Sociales para la Sostenibilidad*

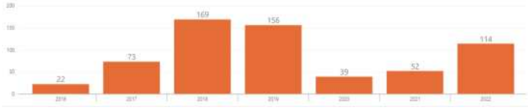
The social aspects evaluated within the sustainability index in this research focus on the protection, access, and equitable distribution of resources and services within a territory. The evaluation of social Key Performance Indicators (KPIs) is based on research presented by (Kapatsa et al., 2023), who define social measurement in terms of intergenerational equity, involving the fair distribution of resources and benefits among present and future generations. The purpose of this social impact assessment is to quantify the social and distributive effects of projects throughout their lifecycle.

The social aspects evaluated for the sustainability index assessment of the operation, conservation, and maintenance of the Chía – Subachoque – Tabio road focus on parameters that estimate the quality and disruptions of traffic service along the route, which can significantly impact population dynamics. This includes evaluating factors such as traffic incidents, road safety, quality of life, cultural impact, and other socio-economic impacts derived from these conditions in surrounding communities.

For the assessment of road safety, statistical records of traffic incidents in each municipality were analyzed over a 5 to 10-year observation period. According to the traffic incidents recorded in the municipality of Chía, it can be deduced that they cause injuries to approximately 89 road users annually, with fatal consequences for 19 road users per year (ANSV, 2023).



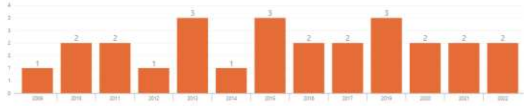
a) History of fatalities



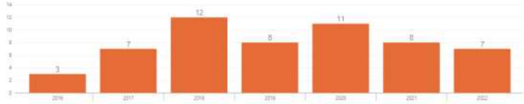
b) Injury history

Figure 19. Road accidents on the roads of the municipality of Chía. Source: Taken from (ANSV, 2023).

In the municipality of Subachoque, the average number of road users injured per year is 8, while the average number of road users fatally injured per year is 2.



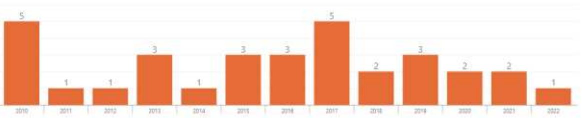
a) History of fatalities



b) Injury history

Figure 20. Road accidents on the roads of the municipality of Subachoque. Source: Taken from (ANSV, 2023).

In the municipality of Tabio, statistics indicate that the number of people injured in traffic incidents is approximately 3 per year, and the number of fatalities is approximately 2 per year.



a) History of fatalities

b) Injury history

Figure 21. Road accidents on the roads in the municipality of Tabio. Source: Taken from (ANSV, 2023).

Based on the analysis of statistical records of traffic incidents in the municipalities of Chía, Subachoque, and Tabio, it can be concluded that there is significant variability in road safety levels among these municipalities. In Chía, a concerning situation is observed with a high number of road users injured and fatalities, indicating the need for urgent interventions to improve road safety. On the other hand, Subachoque shows lower figures compared to Chía, although there are still levels of injuries and fatalities that require attention and preventive measures. In contrast, Tabio has the lowest incidence rates of traffic accidents, suggesting that the safety measures implemented in this municipality could serve as a model to reduce risks on the road. It is important to note that specific policies and actions should be directed towards improving road safety, tailored to the particular needs of each municipality.

The municipality of Chía has approximately 40 residential units inhabited by nearly 130,000 people. Tabio has over 6,000 occupied households with a population of approximately 20,000 people, and in Subachoque, there are about 4,800 households for over 14,000 residents. Table 6 presents statistics on access to essential basic services for each municipality.

Table 6. Percentage of homes without Basic services

Service	*Municipality*	*% Housing without service*
Sewage	Chía	7
	Tabio	35
	Subachoque	33
Aqueduct	Chía	0.75
	Tabio	3
	Subachoque	5
Gas	Chía	11
	Tabio	34
	Subachoque	49
Energy	Chía	
	Tabio	
	Subachoque	
Garbage Collection	Chía	0.63
	Tabio	6
	Subachoque	12

The municipality of Chía has 134 educational centers, with 56% located in rural areas and 44% in urban areas. In Tabio, there are 29 educational institutions, with 59% in rural areas and 41% in urban areas. Subachoque has 24 educational institutions, 75% of which are in rural areas and 25% in urban areas (DANE, 2020).

The cost of care for basic health services in Chía, Tabio and Subachoque between 2014 and 2021 was approximately 568 million pesos, with a monthly average of care for 60 people in general medical services, specialized, dental, diagnostics, therapies and vaccination (Gobernación de Cundinamarca, 2023b).

Travel times for the inhabitants of Chía are approximately 31 minutes from urban areas and less than 25 minutes from rural areas to educational centers. In Tabio, travel times are around 33 minutes and in Subachoque, approximately 15 minutes. To go to work, the inhabitants of Chía take between 26 and 32 minutes, those of Tabio 32 minutes, and those of Subachoque 25 minutes (Gobernación de Cundinamarca, 2023a).

Subachoque has advantages in terms of travel times and distribution of educational institutions, while Chía has a greater educational offer and a more robust health infrastructure. Tabio, although it has educational and health resources, shows a lower quality of services compared to neighboring municipalities.

Cultural measurement in Colombia's regions is carried out through the Public Culture Policy, which seeks to guarantee the right to culture and promote cultural development. These policies are framed in the 1991 Political Constitution, which recognizes culture as an essential foundation of national identity. During this research, it was found that only Chía is in the process of implementing these policies, with periodic evaluations to verify compliance and impact (Gobernación de Cundinamarca, 2020a).

Table 7. Indicadores sociales para la carretera de Chía a Subachoque

Indicator	*Description*	*Evaluation*
Road safety	Evaluation of the road safety level before and after the work, considering the number of accidents, victims and safety measures implemented.	4
Quality of life	Analysis of the impact of the project on the quality of life of local communities, considering aspects such as access to basic services, public health, education and mobility.	4
Citizen participation	Evaluation of the degree of participation of local communities in the planning, design, execution and monitoring of the project.	3
Cultural impact	Identification and assessment of cultural and archaeological heritage sites in the area of influence of the project to minimize their impact.	2

3.2.3 *Economic Key Performance Indicators (KPIs) for Sustainability*

The economic component of sustainability is evaluated by analyzing the life cycle costs and low impact development of a project, considering costs throughout the life cycle and seeking to minimize negative economic impacts, such as maintenance and operation costs (Ametepey et al., 2023). In road infrastructure projects, signaling and protective barriers are constant investments to ensure safety and quality of service, so it is crucial to consider the costs and benefits associated with safety measures, as they can prevent costly accidents and delays in the long term (Kapatsa et al., 2023).

In 2022, the Department of Cundinamarca invested 1.96 billion pesos in the construction, repair, and maintenance of road infrastructure: 1.7 billion in general projects, 8.2 million in maintenance, and 1.7 billion in the improvement of the rural transportation network, in addition to studies and designs (INVIAS, 2022). Although funds were not allocated directly to the municipalities in the study area, mobility was improved in nearby municipalities such as Zipaquirá. With the allocated budget, 125 km of mobility were improved and 845 km of rural roads were built, impacting 85 municipalities, including 0.48 km of pavement, 6.31 km of road maintenance and 4.41 km of improvements (INVIAS, 2022).

Regarding employment, in 2023, the unemployment rate in Cundinamarca was 10.8%, compared to 12.7% in 2022. The employment rate was 59.5%, compared to 59.1% in the previous year, and the overall participation rate was 66.7%, compared to 67.7% in 2022 (DANE, 2023). Between 2014 and 2021, the employment rate in Chía was between 57% and 60%, in Tabio between 56% and 63%, and in Subachoque between 59% and 65%. The unemployment rate in Chía was between 5% and 10%, in Subachoque between 3% and 6%, and in Tabio between 3% and 7% (Gobernación de Cundinamarca, 2021).

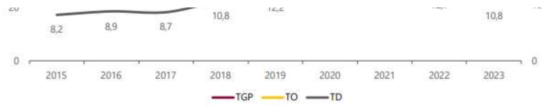


Figure 22. Overall participation, employment and unemployment rates. Cundinamarca from 2015 to 2023. Source: Taken from (DANE, 2023)

The Gross Domestic Product (GDP) is a key indicator of a region's economic performance. In the last report, the Department of Cundinamarca represented 6.24% of the national GDP (DANE, 2022).

The investment in road infrastructure carried out by the Department of Cundinamarca up to 2022 has had a significant impact on regional mobility and connectivity. These investments have contributed to improving employment and unemployment rates, indicating a particular economic boost.

Table 8. Economic indicators for the road from Chía to Subachoque

Indicator	*Description*	*Evaluation*
Construction and maintenance costs	Detailed analysis of the direct and indirect costs associated with the construction and maintenance of the project to assess its long-term economic viability.	3
Employment generation	Quantification of direct and indirect jobs generated during construction and operation of the project to evaluate its impact on the local economy.	4
Impact on productivity	Evaluation of the impact of the project on the productivity of local economic activities, such as agriculture, commerce and tourism..	3
Return on investment	Analysis of the economic profitability of the project, considering costs, benefits and net present value, to evaluate its financial viability.	4

4 RESULTS AND ANALYSIS

After evaluating each of the sustainability Key Performance Indicators (KPIs), the aspects evaluated in each of the sustainability components are regrouped. This regrouping considers the impact, group or resource that the measurement represents. If one or more aspects of the same KPI are related within the grouping, the average is calculated in order to have only three points of reference in the correlation analysis of the evaluated aspects.

The first grouping corresponds to the quality of life criterion, grouping the aspects of air quality, water quality, quality of life and employment generation. These are considered indispensable to ensure that the inhabitants of the study area have access to the minimum resources necessary to carry out their daily activities.

The second grouping was done based on resource management, where the environmental KPI has a significant contribution, while the economic and social KPIs are not as representative in the measurement of sustainability.

The third grouping focuses on the representation of impacts on the three components of sustainability, showing that the social and economic KPI do not have an excellent evaluation, but contribute positively to the measurement of sustainability, while the environmental KPI is not so representative.

The last grouping was done based on resource expenditure or consumption. In this analysis, it is determined that road infrastructure projects have a negative impact on the social component due to the consumption of resources and the slowdown in their recovery. However, this negative measurement is compensated by economic and environmental indicators, which have a good evaluation. Based on the regrouping of KPIs, it can be qualitatively determined that the sustainability index (SI) reaches a medium value.

The weighting assigned to each of the KPIs to estimate the sustainability index of the conservation and operation of the road connecting Chía and Subachoque is established according to recommendations of experts in previous research. The factors that influence the assignment of the weightings consider the sustainability aspects that have greater weight or value in the measurement (Shen et al., 2011; Sumabrata et al., 2022; Suprayoga et al., 2020). Higher weights, considered as positive evaluations, are assigned to aspects that contribute significantly to the sustainability index in terms of economy, environment and society. Lower weights, considered as negative contributions, are assigned to aspects that contribute less economically, environmentally and socially to the sustainability index (Ametepey et al., 2023; Suprayoga et al., 2020).

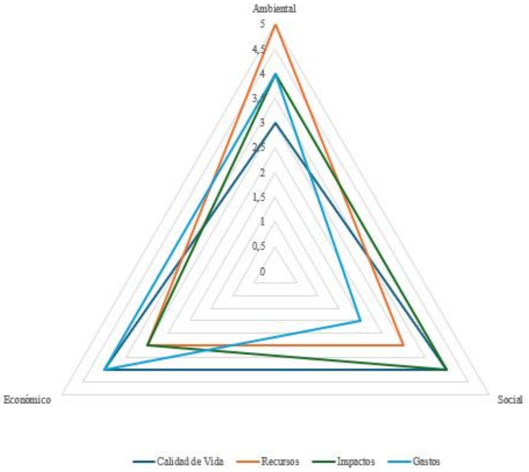


Figure 23. Analysis of the grouping of the aspects evaluated in sustainability

According to the referenced methods and the analysis of the regroupings of the KPIs, it is estimated that the weighting for the environmental parameter, having the largest evaluation scale, is 60%. The social parameter, which presents the greatest dispersion and a lower evaluation, receives a weighting of 10%. The economic aspect, with an evaluation trend from good to fair, is assigned a weighting of 30%.

(Del Rosario & Traverso, 2023; Sumabrata et al., 2022) recommend that the sustainability index (SI) be calculated as the sum of the averages of the environmental, social and economic indicators (see equation 1). The sustainability KPIs represent the operating conditions of geotechnical structures and road layouts within the social system to which they belong.

The Sustainability Index (SI) varies between 1 and 5. An SI close to 5 indicates that road infrastructure has a lower environmental impact during construction, operation and management, thanks to lower greenhouse gas emissions, less soil and water pollution, and a reduction in biodiversity loss. Economically, this translates into an efficient use of resources such as energy, water and construction materials. Socially, it implies the promotion of community participation in the planning and design of works, prioritizing road infrastructure needs for the economic and productive benefit of the region (Reddy et al., 2024; Shen et al., 2011).

The SI is closely related to the resilience of road infrastructure and geotechnical works. High sustainability (SI close to 5) implies that structures are not only environmentally friendly and resource efficient, but also able to absorb, adapt and recover from disruptive events, such as climatic changes or significant environmental events. This ensures that road infrastructures are more resilient and durable in the face of possible future events (Bocchini & Frangopol, 2011; Reddy et al., 2024).

$$IS = 0.6 * \overline{KIP}_{Environmental} + 0.1 * \overline{KIP}_{Social} + 0.3 * \overline{KIP}_{Economic} \qquad (1)$$

The arithmetically estimated SI is 3.75, indicating that the road layout and geotechnical structures of the road connecting the municipality of Chía to Subachoque are moderately close to achieving sustainability. There is agreement between both evaluations in contrast to the qualitative analysis conducted.

On the other hand, in terms of risk management, an SI of 3.75 would indicate a significant need to establish a plan for effective risk management, which would be closely related to the resilience index. This measurement also identifies the system's recovery capacity in the face of adverse events that could jeopardize its proper functioning.

5 CONCLUSIONS

Research on the sustainability of road infrastructure, based on the measurement of key performance indicators (KPIs), is crucial to understand the environmental, social and economic impact of projects such as the road between Chía and Subachoque. Shen et al. (2011) highlight the importance of considering multiple perspectives when evaluating these indicators. The proposed methodology is based on expert evaluation and analysis of perceptions of each indicator, providing a more complete understanding of the sustainability of road infrastructure.

In the social domain, protection, access and equitable distribution of resources and services are evaluated, with road safety as a critical aspect in Chía. Differences in access to basic and educational services, as well as travel times, highlight disparities between municipalities. Public policies to promote cultural development are essential, with progress in Chía and the need for greater attention in Subachoque and Tabio.

Economically, sustainability is evaluated by considering the costs and benefits throughout the life cycle of the project. Investment in road infrastructure in Cundinamarca has improved regional mobility, reduced unemployment and contributed to the national Gross Domestic Product.

Geotechnical works are fundamental for the sustainability of road infrastructure. The sustainability index highlights the importance of constant maintenance and monitoring to prevent failures that could negatively affect traffic and have economic, social and environmental repercussions. Regular maintenance and adequate supervision ensure the durability and safety of road infrastructure.

Comprehensively assessing sustainability KPIs provides a solid basis for informed decisions that promote long-term sustainability, ensuring balanced development and the well-being of affected communities (Bocchini & Frangopol, 2011; Reddy et al., 2024).

Moreover, resilience and sustainability of rural roads are closely related, since an infrastructure capable of withstanding and recovering quickly from disruptive events also tends to be more sustainable. Implementing resilience-enhancing practices, such as regular maintenance and constant assessment of the condition of structural elements, promotes greater durability and resource efficiency. In this way, rural roads can not only effectively address environmental and operational challenges, but also ensure their long-term functionality and service, contributing significantly to the sustainable development of rural communities (Pineda et al., 2024).

6 REFERENCIAS

Alcaldía de Bogotá. (2022). *Crecimiento Urbano, Crecimiento Económico y Finanzas Territoriales en la Región Bogotá Cundinamarca*. Crecimiento Urbano, Crecimiento Económico y Finanzas Territoriales En La Región Bogotá Cundinamarca. https://www.sdp.gov.co/sites/default/files/crecimiento_urbano_0.pdf

Alcaldía Municipal de Chía. (2024). *Datos – Alcaldía Municipal de Chía*. https://chia-cundinamarca.gov.co/web/2023/12/28/datos-abiertos/

Alcaldía Municipal de Subachoque. (2024). *Transparencia*. https://www.subachoque-cundinamarca.gov.co/transparencia

Alcaldía Municipal de Tabio. (2024). *Transparencia*. http://www.tabio-cundinamarca.gov.co/transparencia

Ametepey, S. O., Aigbavboa, C. O., & Thwala, W. D. (2023). Sustainability Criteria and Indicators for Road Infrastructure Projects. In *Sustainable Road Infrastructure Project Implementation in Developing Countries: An Integrated Model*. https://doi.org/10.1108/978-1-83753-810-220231006

ANSV. (2023). *Histórico víctimas | ANSV*. https://ansv.gov.co/es/observatorio/estad%C3%ADsticas/historico-victimas

Ausilio, E., & Zimmaro, P. (2017). Landslide characterization using a multidisciplinary approach. *Measurement: Journal of the International Measurement Confederation*, *104*. https://doi.org/10.1016/j.measurement.2016.01.009

Basu, D., & Lee, M. (2022). A combined sustainability-reliability approach in geotechnical engineering. In *Risk, Reliability and Sustainable Remediation in the Field of Civil and Environmental Engineering*. https://doi.org/10.1016/B978-0-323-85698-0.00029-0

Batool, K., Alshameri, B., Raza, F., Haider, A., & Ali, M. (2023). Normalization of geotechnical sustainability assessment tool (Geo-SAT) using multiple criteria decision analysis for dams. *Environment, Development and Sustainability*. https://doi.org/10.1007/s10668-023-03442-3

Bocchini, P., & Frangopol, D. M. (2011). Resilience-driven disaster management of civil infrastructure. *ECCOMAS Thematic Conference - COMPDYN 2011: 3rd International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering: An IACM Special Interest Conference, Programme*.

Calvente, A. (2007). Resiliencia: un concepto clave para la sustentabilidad. *… Difusión e Investigación En Sustentabilidad …*.

CEPAL. (2019). ODS 13: Adoptar medidas urgentes para combatir el cambio climático y sus efectos en América Latina y el Caribe. *Estadísticas Regionales Clave Sobre El ODS 13*. https://www.cepal.org/sites/default/files/static/files/ods13_c1900799_press.pdf

CEPAL. (2021a). Objetivo de Desarrollo Sostenible (ODS) 7: ASEQUIBLE Y NO CONTAMINANTE. *Panorama Regional*.

CEPAL. (2021b). *Objetivo de Desarrollo Sostenible (ODS) 9: Construir infraestructuras resilientes, promover la industrialización inclusiva y sostenible y fomentar la innovación*.

CEPAL. (2023). *Objetivo de Desarrollo Sostenible (ODS) 11: Lograr que las ciudades y los asentamientos humanos sean inclusivos, seguros, resilientes y sostenibles*. ODS 11 Panorama Regional 2023. https://www.cepal.org/sites/default/files/c2300206d_ods_11_web.pdf

Chisco, I. A. (2015). *Infraestructura Sector educación*.

CONGRESO DE COLOMBIA. (1993). *LEY 99 DE 1993*. http://www.secretariasenado.gov.co/senado/basedoc/ley_0099_1993.html

DANE. (2012). *Geovisor de Servicios Web Geográficos - Gasto Protección Ambiental*. https://geoportal.dane.gov.co/geovisores/territorio/servicios-web-geograficos/?cod=96

DANE. (2019a). *Censo Nacional de Población y Vivienda 2018 - Subachoque*. Https://Sitios.Dane.Gov.Co/Cnpv/#!/.

DANE. (2019b). *Censo Nacional de Población y Vivienda 2018 - Tabio*. Https://Sitios.Dane.Gov.Co/Cnpv/#!/.

DANE. (2019c). *CENSO Nacional de Poblacional y Vivienda 2018 - Chía*. Https://Sitios.Dane.Gov.Co/Cnpv/#!/.

DANE. (2019d, August 30). *Información general*. Explorador de Datos CENSO NACIONAL DE POBLACIONAL Y VIVIENDA . https://sitios.dane.gov.co/cnpv/#!/

DANE. (2020). *Geoportal del DANE - Geovisor Consulta de Sedes Educativas del SISE*. https://geoportal.dane.gov.co/geovisores/sociedad/consulta-geosise/

DANE. (2022). *Geoportal del DANE - Geovisor PIB Departamental Base 2015-2022*. https://geoportal.dane.gov.co/geovisores/economia/pib-departamental/

DANE. (2023). *Boletín técnico Gran Encuesta Integrada de Hogares (GEIH) 2023*.

Das, J. T., Samuel, R. A., George, A. M., Chakraborty, S., Bheemasetti, T. V., & Puppala, A. J. (2018). *Establishing a Threshold Sustainability Index for a Geotechnical Construction*. https://doi.org/10.1061/9780784481615.018

Del Rosario, P., & Traverso, M. (2023). Towards Sustainable Roads: A Systematic Review of Triple-Bottom-Line-Based Assessment Methods. *Sustainability*, *15*(21), 15654. https://doi.org/10.3390/su152115654

Gallice, G. R., Larrea-Gallegos, G., & Vázquez-Rowe, I. (2019). The threat of road expansion in the Peruvian Amazon. *ORYX*, *53*(2). https://doi.org/10.1017/S0030605317000412

GBIF, & CAR. (2023). *CAR - Corporación Autónoma Regional de Cundinamarca*. https://www.gbif.org/publisher/47380c8a-0edd-4036-b1bc-d852cba8232f/metrics

Gobernación de Cundinamarca. (2020a). *Estado de la Política Pública de Cultura. 2017 en Cundinamarca - Web Map*. https://mapasyestadisticas-cundinamarca-map.opendata.arcgis.com/maps/746d19fa49f34bd896e75ff2072d62e9/explore?location=4.875264%2C-74.094692%2C11.00

Gobernación de Cundinamarca. (2020b). *Informe Anual del Estado de los Recursos Naturales y del Ambiente del departamento de Cundinamarca*.

Gobernación de Cundinamarca. (2021). *Encuesta Multipropósito - Empleabilidad*. https://experience.arcgis.com/experience/51beb39022824950884ace9e29d191ef#data_s=id%3AdataSource_4-0%3A3

Gobernación de Cundinamarca. (2023a). *Encuesta Multipropósito - Movilidad*. https://experience.arcgis.com/experience/51beb39022824950884ace9e29d191ef#data_s=id%3AdataSource_4-0%3A12

Gobernación de Cundinamarca. (2023b). *Encuesta Multipropósito - Salud*. https://experience.arcgis.com/experience/51beb39022824950884ace9e29d191ef#data_s=id%3AdataSource_4-0%3A9

Gobernación de Cundinamarca. (2023c). *MAPAS Y ESTADÍSTICAS DE CUNDINAMARCA*. https://mapas.cundinamarca.gov.co/

Gobernación de Cundinamarca. (2024). *“CUNDINAMARCA, ¡REGIÓN QUE PROGRESA!” 2020-2024 SECRETARÍA DEL AMBIENTE NIDIA CLEMENCIA RIAÑO CONTENIDO*.

Google Maps. (2024). *de Chía, Cundinamarca a Subachoque, Cundinamarca - Google Maps*. https://www.google.com/maps/dir/Ch%C3%ADa,+Cundinamarca/Tabio,+Cundinamarca/Subachoque,+Cundinamarca/@4.9051191,-74.194139,12z/data=!3m1!4b1!4m20!4m19!1m5!1m1!1s0x8e3f878dd475a989:0x4211096980b5302!2m2!1d-74.050918!2d4.864758!1m5!1m1!1s0x8e4079183fa5cb65:0x20097a44cc3abaea!2m2!1d-74.096358!2d4.916962!1m5!1m1!1s0x8e407e600ef4fcf5:0x3fac3f08e84f5c2e!2m2!1d-74.172465!2d4.929001!3e0?hl=es&entry=ttu

IDEAM. (2017). *SUELO Y TIERRA*. http://www.ideam.gov.co/web/ecosistemas/suelo-y-tierra

IDEAM, Fundación Natura, PNUD, MADS, DNP, & CANCILLERÍA. (2022). *INVENTARIO DEPARTAMENTAL DE GASES EFECTO INVERNADERO Y CARBONO NEGRO-2018 4 5 INVENTARIO DEPARTAMENTAL DE GASES EFECTO INVERNADERO Y CARBONO NEGRO-2018 2*. www.cambioclimatico.

INVIAS. (2022). *SEGUIMIENTO INVERSIÓN CUNDINAMARCA*.

IQAir. (2024). *Contaminación del aire de AireCiudadano COLCHIA SIMBIOT 6d4d88, Chía, Colombia: Índice de la Calidad del Aire (ICA) en tiempo real*. https://aqicn.org/station/colombia-ch%C3%ADa-aireciudadano-colchia-simbiot-6d4d88/es/#/z/11.2

Kapatsa, C., Kavishe, N., Maro, G., & Zulu, S. (2023). The Identification of Sustainability Assessment Indicators for Road Infrastructure Projects in Tanzania. *Sustainability*, *15*(20).

Laurance, W. F., Goosem, M., & Laurance, S. G. W. (2009). Impacts of roads and linear clearings on tropical forests. In *Trends in Ecology and Evolution* (Vol. 24, Issue 12). https://doi.org/10.1016/j.tree.2009.06.009

Lu, X., Liao, W., Fang, D., Lin, K., Tian, Y., Zhang, C., Zheng, Z., & Zhao, P. (2020). Quantification of disaster resilience in civil engineering: A review. *Journal of Safety Science and Resilience*, *1*(1). https://doi.org/10.1016/j.jnlssr.2020.06.008

Ministerio de Ambiente y Desarrollo Sostenible. (2017). *Política Nacional de Cambio Climático*. Https://Www.Minambiente.Gov.Co/Wp-Content/Uploads/2022/01/9.-Politica-Nacional-de-Cambio-Climatico.Pdf.

Ministerio De Transporte, ⎱. (2017). *Agradecimientos*.

Ortega, R. E., Comar, V., Luri, C. B., Rosa, L. I. A., Ortega, M. E., & Alapont, A. B. (2001, September 16). *ECOSISTEMAS Y POLÍTICAS PÚBLICAS*. Ortega.

Pineda, J. A., Larranaga, S. C., & Carmona, J. (2024). Multi-criteria Analysis for the Estimation of Resilience Indices in Geotechnical Systems: Application to Earth-Retaining Structures. *The International Journal of Architectonic, Spatial, and Environmental Design*, *18*(2), 43–71. https://doi.org/10.18848/2325-1662/CGP/v18i02/43-71

Quiroga Martínez, R. (2009). *Guí a metodológica para desarrollar indicadores ambientales y de desarrollo sostenible en países de América Latina y el Caribe manuales*.

Reddy, K. R., Janga, J. K., & Kumar, G. (2024). Sustainability and Resilience: A New Paradigm in Geotechnical and Geoenvironmental Engineering. *Indian Geotechnical Journal*. https://doi.org/10.1007/s40098-024-00899-5

Shen, L., Wu, Y., & Zhang, X. (2011). Key Assessment Indicators for the Sustainability of Infrastructure Projects. *Journal of Construction Engineering and Management*, *137*(6), 441–451. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000315

Sumabrata, R. J., Iskandar, D., & Abiyoga, R. (2022). Evaluation of the Sustainability Indicator for Road Infrastructure in Indonesia. *Civil Engineering and Architecture*, *10*(6). https://doi.org/10.13189/cea.2022.100628

Suprayoga, G. B., Bakker, M., Witte, P., & Spit, T. (2020). A systematic review of indicators to assess the sustainability of road infrastructure projects. *European Transport Research Review*, *12*(1). https://doi.org/10.1186/s12544-020-0400-6

United Nations. (2023, August 24). *Acerca de la Agenda 2030 para el Desarrollo Sostenible*. Https://Www.Cepal.Org/Es/Temas/Agenda-2030-Desarrollo-Sostenible/Acerca-La-Agenda-2030-Desarrollo-Sostenible.

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