



SYSTEMIC APPROACH TO THE INFLUENCE OF CLIMATE ON THE DYNAMICS OF THE MUNICIPALITY OF PASTO, COLOMBIA*

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ABSTRACT

The impact of climate change in intermediate cities is a topic of growing interest on Latin America. This study analyzed the influence of climate in the city of Pasto, Colombia. Based on several land use planning methodologies, we defined the main urban elements that affect the city's territorial dynamics. Subsequently, we employed a structural analysis to identify the main relationships among the urban elements. Using direct and indirect classification based on the method of cross-impact matrices applied multiplication for a classification (MICMAC) and the Delphi method, we determined the dependencies and influences of the urban elements integrated in a systemic model of 12 positive and 8 negative loops that relate climate, energy, and culture as power elements over the city's economy, health, education, environment, functionality, demography, and security, all of which are articulated by governance as the key element, with results applicable to other cities in the region.

Keywords: Urban system; systemic approach; structural analysis; conceptual model; climate; climate change.

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ENFOQUE SISTÉMICO DE LA INFLUENCIA DEL CLIMA EN LA DINÁMICA DEL MUNICIPIO DE PASTO, COLOMBIA

RESUMEN

El impacto del cambio climático en ciudades intermedias es un tema de creciente interés en América Latina. Este estudio analizó la influencia del clima en la ciudad de Pasto, Colombia. Basados en diversas metodologías de planificación del uso del suelo, definimos los principales elementos urbanos que afectan la dinámica territorial de la ciudad. Posteriormente, empleamos un análisis estructural para identificar las principales relaciones entre los elementos urbanos. Utilizando una clasificación directa e indirecta basada en el método de matrices de impacto cruzado con multiplicación aplicada para la clasificación (MICMAC) y el método Delphi, determinamos las dependencias e influencias de los elementos urbanos integrados en un modelo sistémico de 12 bucles positivos y 8 negativos que relacionan el clima, la energía y la cultura como elementos poderosos sobre la economía, salud, educación, medio ambiente, funcionalidad, demografía y seguridad de la ciudad, todos los cuales están articulados por la gobernanza como el elemento clave, con resultados aplicables a otras ciudades de la región.

Palabras clave: Sistema urbano; enfoque sistémico; análisis estructural; modelo conceptual; clima; cambio climático

INTRODUCTION

Cities are social constructions that have the greatest impact on climate change (CC) and are the first to bear consequences [1], mainly because they concentrate on people, built environments, and economic dynamics [2]. Urbanization induces anthropogenic warming of the system, together with extreme weather events that will be more intense and frequent, with stronger heat waves (warmer days and nights), more intense average and heavy rainfall, with higher surface runoff and increased tropical storm surges and sea level changes [3]. In Latin America, climate change affects more than 50 % of the population living in intermediate cities due to increased precipitation, landslides, droughts, food shortages and health risks [2].

This research seeks to recognize the systemic relations between climate and the urban elements of the municipality of Pasto, in Colombia, an intermediate city, with a population of 460,400 [4], and the active dynamics of economic development and population growth, located in the Andean cordillera near the border with Ecuador. To identify the urban elements and their relations in the city of Pasto, we developed the following methodology: document review, expert survey (Delphi method), application of structural analysis and construction of a causal diagram of the system's dynamics, to recognize the territory as a system and infer its behavior. Pasto is compatible with other Latin American cities that share common characteristics, such as very cold climates in high mountainous terrain and valleys, emerging economies, and rapid changes in population dynamics.

This article is composed of three sections. The first section introduces the main elements of the urban structure of the municipality of Pasto. The second section identifies the relationships between urban elements using MICMAC and Delphi methods. The third section presents a dynamic system causal diagram that describes the roles of the elements and their interactions and discusses the most relevant positive and negative feedback loops that may be acting in the urban system under the influence of climate.

1. MATERIALS AND METHODS

1.1 The municipality of Pasto

Pasto is located in the southeast of Colombia, in the department of Nariño, between the coordinates $1^{\circ}12'0''\text{N}$ and $77^{\circ}16'0''\text{W}$, over an area of 109,555 ha, of which 2,367 ha corresponds to the city of San Juan de Pasto (urban area) as the municipal and departmental capital city. According to [5], Pasto is classified as an intermediate city (between 100,000 and 1 million inhabitants) with 460,500 inhabitants, of whom 86 % live in urban areas and 14 % in rural areas, mainly due to rural and regional

immigration [4], in search of job opportunities, affordable housing, health, education, among others [6].

Climate change reduces regional economies, modifies the social structure, exacerbates poverty, and causes the migration of the most vulnerable people [7], especially those living on the coasts and steep slopes [8]. In a scenario where Pasto becomes a recipient of the migrant population, the city will have to support the demand for water, energy, goods, and ecosystem services.

The rainfall regime is monomodal in the Amazon province and bimodal in the Norandean province, and together with the mountainous morphology of high slopes, including the Galeras volcanic complex, provides the municipality with great biodiversity and disaster risks associated with earthquakes, floods and landslides. The latter two were increased by climatic events of the cold phase of El Niño-Southern Oscillation (ENSO), which occurred in 2010 and 2011, and by the warm phase of La Niña in 2015 and 2016 [9].

1.2 Selection of the systemic approach

We used the MICMAC method [10] as an interpretative structural model that allows the establishment of relationships among the elements according to their level of influence and dependencies within the system [11].

1.3. Identification of urban elements

The influence of climate on the urban elements depends on multiple factors. These include climate, technology, construction, open areas, socioeconomic characteristics, and vulnerability of the population to climate change [12]. Some authors [13] considered key variables of the urban system for health and well-being, whereas others [14] used variables of population growth, infrastructure, urban sprawl, public transportation, housing, disadvantaged communities, and vulnerability to climate change.

There are several internationally recognized methods of territorial planning that use different elements and variables. To provide a comprehensive view of the key components that define the urban structure of Pasto, we reviewed four of these spatial planning tools: the ISO 37120 standard [15], City Resilience Index [16], Emerging and Sustainable Cities Initiative (ESCI) [17], and Making Cities Resilient Global Campaign [18]. By comparing the methodologies described above, we were able to identify the common elements that existed between them, as shown in Table 1.

Table 1. Selected urban elements for territorial planning

| Elements | Description |
|---------------------|---|
| Environment (Env) | Environmental quality of natural resources |
| Culture (Cul) | Cultural events, customs, ethnic groups, and traditions |
| Health (Hea) | Influence on public health at physical, mental, and social level |
| Education (Edu) | Level, coverage, and quality of the formal education provided |
| Demography (Dem) | Number of residents, distribution, and migratory processes |
| Functionality (Fun) | Urban interventions, coverage, and quality of public services |
| Risks (Ris) | Population exposure to disaster risk factors |
| Climate (Cli) | Conditions of precipitation, temperature, and climate change |
| Economy (Eco) | Processes of competitiveness and productivity of the economic sectors |
| Governance (Gov) | Leadership of public institutions |
| Energy (Ene) | Type and source of energy available |
| Security (Sec) | Situations of violence and insecurity |

Source: own elaboration.

1.4. Systemic relations from the MICMAC method

With the urban elements identified, we collected the perspectives of six local professionals with experience in different topics (economy, entrepreneurship, health, politics, environment, and social organization) who independently filled out a Matrix of Direct Impacts according to the Delphi method [19]. From this matrix, we determined the levels of influence and dependency of the elements, classifying them as explanatory, connective, dependent, and autonomous.

1.5. Development of the causal diagram

Establishing relationships in social systems is a complex task because they have positive and negative feedback processes [20] that are governed by self-organization, self-regulation, self-repair, self-observation, and intelligence (Meléndez, cited by [21]). To reduce the complexity, the relationships can be represented by diagrams [22] by adding linear and circular models [20]. In this sense, system dynamics articulates the two ways of representing the systems described above to perform simulations [23]. Based on the diagrams of the influences generated by the MICMAC software, we developed a causal diagram of the municipality of Pasto, using positive and negative feedback loops.

2. RESULTS

2.1. Urban elements of the municipality of Pasto

Once the urban elements were defined, we asked six local experts (specialists in finance, social responsibility and sustainability, international relations, public health, development and water resources) to fill in the Direct Impact Matrix (double-entry square matrix) to obtain their perception of how the urban elements identified in Table 1 relate to each other, based on the following question [10]: How does a given element in the left column affect each of the elements in the top row of the matrix? The answers considered the following numerical options: (0) if there is no influence; (1) if the influence is weak; (2) if the influence is medium; (3) if the influence is strong; and (P) potential influence, if it is believed that the influence could be important in the future.

The experts’ responses were averaged and consolidated, as presented in Table 2.

Table 2. Matrix of direct relations identified by experts in the municipality of Pasto.

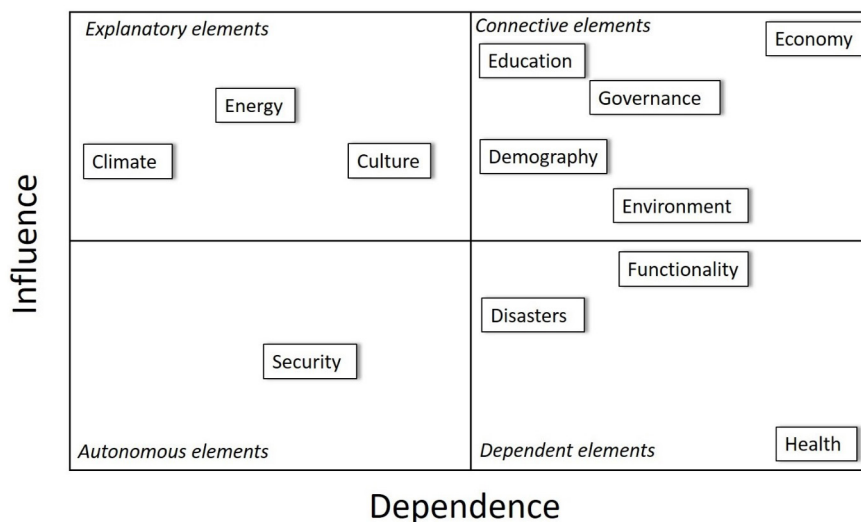
| | Environment | Culture | Health | Education | Demography | Functionality | Risks | Climate | Economy | Governance | Energy | Security | |
|---------------|---------------------|---------|--------|-----------|------------|---------------|-------|---------|---------|------------|--------|----------|--------------------|
| Environment | ■ | 2 | 3 | 1 | 2 | 3 | 2 | 2 | 3 | 2 | 2 | 1 | Level of influence |
| Culture | 3 | ■ | 1 | 2 | 3 | 2 | 3 | 2 | 2 | 2 | 2 | 2 | |
| Health | 0 | 1 | ■ | 2 | 2 | 1 | 1 | 0 | 2 | 2 | 0 | 1 | |
| Education | 3 | 3 | 2 | ■ | 3 | 3 | 2 | 2 | 3 | 3 | 3 | 3 | |
| Demography | 3 | 2 | 3 | 2 | ■ | 2 | 3 | 2 | 2 | 2 | 2 | 2 | |
| Functionality | 2 | 1 | 3 | 2 | 2 | ■ | 2 | 1 | 3 | 2 | 2 | 1 | |
| Risks | 2 | 2 | 3 | 2 | 2 | 1 | ■ | 1 | 3 | 2 | 1 | 1 | |
| Climate | 3 | 2 | 3 | 2 | 2 | 3 | 3 | ■ | 3 | 2 | 2 | 0 | |
| Economy | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | ■ | 3 | 3 | 3 | |
| Governance | 3 | 2 | 3 | 3 | 2 | 3 | 2 | 2 | 3 | ■ | 2 | 2 | |
| Energy | 3 | 2 | 2 | 2 | 1 | 3 | 2 | 2 | 3 | 3 | ■ | 2 | |
| Security | 1 | 2 | 2 | 2 | 1 | 1 | 1 | 0 | 3 | 2 | 1 | ■ | |
| | Level of dependence | | | | | | | | | | | | |

Source: own elaboration.

In this sense, the matrix allows different scores for the influence of A on B compared with the influence of B on A. Thus, the horizontal summation identifies the level of influence of each element on the others, and the vertical summation identifies the level of dependence of each element on the others.

From the matrix of direct relationships in the MICMAC software, we generated a map of indirect influences and dependencies, which classified the urban elements as explanatory, connective, dependent, and autonomous, as shown in Figure 1.

Figure 1. Map of indirect influences and dependences for the city of Pasto



Source: own elaboration.

2.1.1 Explanatory or power elements

The elements climate, energy and culture are explanatory, since their behavior strongly influences the evolution of the other elements, but they do not depend significantly on the other elements of the system. Global greenhouse gas (GHG) emissions are altering the climate, mainly from China, the United States, India, Russia, and Japan (59.3 %), the European Union and India (7 %) [24]. The global effects of climate change greatly affect Latin America, despite its relatively low GHG emissions [25].

Colombia, for instance, emits 0.291 % of the total GHG, from which Pasto contributes only 0.000715 %. These emissions correspond to public and private transportation (58 %), Agriculture, Forestry and Other Land Use (AFOLU) sector (18 %), solid waste management (13 %), and the rest to other sectors, for a total of 643,475 tons of CO₂eq [6]. In the context of this study, we subordinate the local effects of air pollution and urban heat island to the broader impact of temperature increases due to projected climate change in the municipality. We related these two local aspects to the public health and functionality elements of Pasto.

Most of the energy in Pasto originates from other Colombian cities. Therefore, the local government only influences its commercialization. Energy demand is 1,004,743 Barrels of Oil Equivalent (BOE), where 85 % comes from oil (gasoline, diesel, and LPG), with transportation being the largest consumer [26]. The local contribution of electric power is between 15 % and 20 %, which comes from two small hydroelectric plants,

the rest comes from the interconnected Colombian electricity market (hydroelectric and thermo-electric plants) (This information was provided personally in 2019 by Centrales Eléctricas de Nariño).

Culture corresponds to historical activities transmitted from generation to generation, which define the identity of the people. In this sense, the independence of New Granada between 1808 and 1819, which pitted royalists (supported by Pasto) against patriots (Simón Bolívar's army), significantly marked the cultural identity of Pasto [27], [28], [29], [30]. This dispute isolated Pasto from the rest of Colombia, generating a commercial, labor, and cultural disconnection that remains today [5]. However, the culture and traditions of the municipality have contributed to strengthening the social fabric and its development.

2.1.2 Connecting elements

These elements are as influential as they are dependent, and therefore, can be managed internally through feedback processes capable of overriding or enhancing any action that attempts to modify the system [31]. At the local level, this category includes the elements of governance, education, population, environment, and economy. In the context of climate change, the proper management of these elements can increase resiliency and reduce the effects of climate change, in addition to generating greater social, economic and environmental returns for the city [32].

Governance establishes a relationship between government and citizens [33]. In Pasto, the new governance began to consolidate from 1995, with the implementation of community participatory processes [34], which contributed to economic, institutional, and administrative growth [5]. However, corruption, social inequality, drug trafficking, and the presence of armed groups, among other factors, impede the systemic management of the municipality as an engine of multidimensional development.

Primary and secondary education levels in Pasto are among the best in the country [35]. However, in tertiary and graduate education, the coverage is only 3.4% [6]. This deficit impedes the advancement of development and innovation processes, which is the key to boosting work, productivity, wages, and professional advancement [36], in addition to responding timely and comprehensibly to public contingencies, such as what happened with the Covid-19 pandemic [37].

In demographic terms, Pasto has a population of 460,00 inhabitants, which consolidates it as an intermediate city [5], with a population growth rate that has been decreasing from 2.6 % (1993-2005) to 1.5 % (2005-2018), similar to the Frizz index, which decreased from 222 to 80 in the same period [38], giving rise to a mature population structure [39]. Although the population is growing more slowly, it is mainly responsible for the deterioration of the local natural resources.

Pasto has a great variety of ecosystems because of its location in the Amazonian and Norandean provinces, where the Putumayo (tributary of the Amazon basin), Pasto, and Bobo rivers (tributaries of the Pacific basin) make up the local environmental strategic system, such as wetlands, moorlands, and water recharge areas. There are ten endemic moorlands shared with other municipalities that occupy 17,218 ha, including La Corota (Flora Sanctuary), and the Galeras Volcano (Flora and Fauna Sanctuary). In addition, there are ten wetlands, including La Cocha (Ramsar Wetland) [40]. These systems produce 538.7 mm³/year of water [41], which is essential for the functioning of urban systems. However, climate change and atmospheric nitrogen may limit the environmental services they provide [42], and therefore, the economy.

At the local level, the tertiary sector contributes 85 % of the Gross Domestic Product (GDP), with personal and domestic care services, and automobile repair being the most significant contributors. The secondary sector contributes 11.41 %, primarily from the manufacturing industry, while the primary sector contributes 3.59 %, mainly from the agricultural sector [43]. This makes Pasto a predominantly commercial municipality with an incipient industrial development [44]. At the departmental level, Pasto contributes more than 50 % of the GDP [45], solidifying its position as the capital of Nariño.

2.1.3 Dependent elements

This group is highly dependent and contains few influential elements [31]. The urban elements identified in this category were disaster risks, functionality, and public health. Among the main disaster risks, extreme weather, floods, landslides, and forest fires were identified. Floods and landslides are associated with heavy rainfall, steep slopes, impermeable soil, loss of vegetation cover, occupation of natural watercourses, and accumulation of garbage in sewage systems. However, the construction and rehabilitation of 57 km of sewerage [46] significantly reduces risks, but climate change may worsen them.

In terms of functionality, the compact city urban model adopted in Pasto was included, aiming to restrict urban sprawl, which preserves land for agriculture and livestock. This model can contribute to reducing GHG emissions, creating a stable and dynamic social economy [47], reducing heat islands [48], and seasonal epidemics [49].

According to local conditions, disease prevalence reports [50], and low levels of air pollution [51], the incidence of acute respiratory infections (ARI) and acute diarrheal diseases (ADD) are the most sensitive to climate variation. Climate change, air pollution, and urban planning can contribute to the evolution of public health. [52]. Prior to the pandemic, experts identified health as a dependent element. However, the pandemic altered the socioeconomic structure of Pasto, leading to the assumption that this element

was underestimated. However, the implementation of safety standards, virtual work, and vaccinations allowed a return to normality, confirming its initial classification.

2.1.4 Autonomous elements

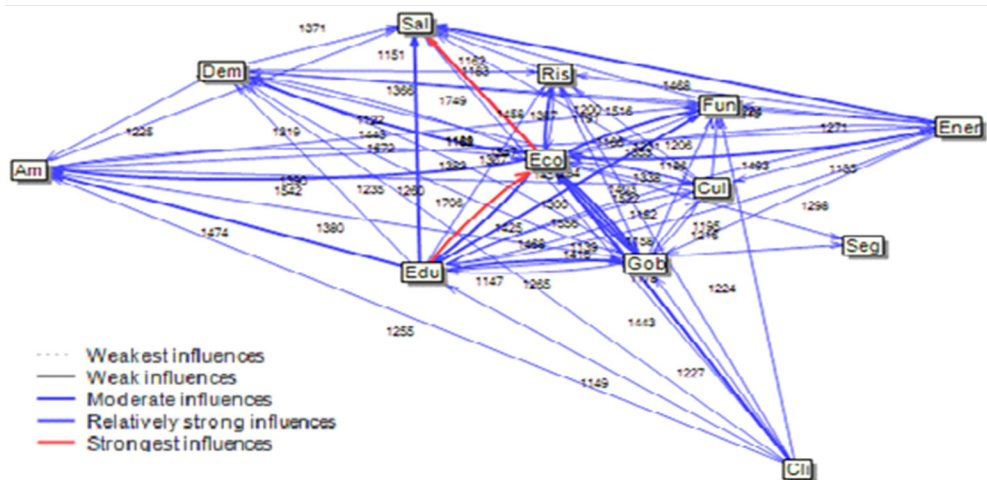
Autonomous elements have little influence on the system. In this category, we identify the security element. In the context of COVID-19, the relationship between security and the economy became evident, especially due to the high unemployment rates (23.4 %) reached in Colombia and, therefore, the increase in urban violence. Although it has decreased at the onset of the pandemic, it is expected to worsen in the long term [53]. Therefore, it was included in the structural analysis.

2.2. Conceptual model

Using MICMAC software, we constructed a Potential Indirect Influence Diagram that shows the level of influence of the urban elements by classifying them as the strongest, relatively strong, moderate, weak, and weakest. This diagram can be generated for different densities. Strong relationships were observed at lower densities (5 %) and weak relationships were observed when the density increased (100 %).

At the local level, the potential indirect influence diagram shows strong relationships between economy, health, and education, followed by governance, climate, environment, functionality, demographics, and energy, and, to a lesser extent, security and economy, as shown in Figure 2.

Figure 2. Potential indirect influence diagram (50 % density)

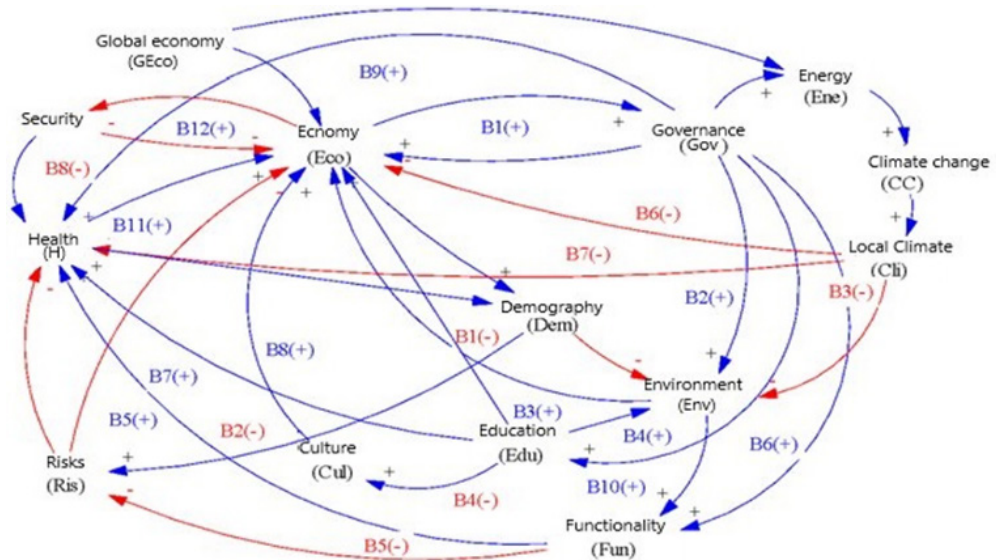


Source: own elaboration.

However, this diagram does not show how an element reacts to a perturbation, which is important for recognizing the evolution of a system. According to [54], a relationship is positive if the affected element reacts in the same direction as the perturbing element and negative if the reaction is in the opposite direction.

Therefore, based on the most significant relationships of influence in the context of the system dynamics, we developed a causal diagram representing the interactions of the urban system, as shown in Figure 3.

Figure 3. Causal diagram



Source: own elaboration

The causal diagram had 12 positive loops (B) and eight negative loops (Table 3). Loops are closed chains of relationships defined as positive (the number of negative relationships is even) and negative (the number of relationships is odd). Thus, negative loops are desirable to achieve regulated outcomes, whereas positive loops cause a system to grow, evolve, or collapse. Therefore, the behavior of the system depends on the most dominant loop at any given time [54].

Positive loops tend to destabilize the system, whereas negative loops tend to stabilize it. Systemic articulation in public management generates virtuous circles capable of promoting equitable growth, empowering communities and liveable spaces, and reducing pollution [55] to foster well-being, prosperity, equity, justice, and peace [56].

Table 3. Loops of the Pasto Urban System

| Loops | Positives | Negatives |
|-------|---------------------------------|--|
| B1 | Eco - Gov - Eco | Eco - Dem - Env - Eco |
| B2 | Gov - Env - Eco - Gov | Dem - Ris - Eco - Dem |
| B3 | Gov - Edu - Eco | Cli - Env - Eco - Gov - Ene - CC - Cli |
| B4 | Gov - Edu - Env - Eco - Gov | Cli - Env - Fun - H - Eco - Gov - Ene - CC - Cli |
| B5 | Gov - Fun - Ris - Eco - Gov | Cli - Env - Fun - Ris - Hea - Eco - Gov - Ene - CC - Cli |
| B6 | Gov - Fun - Hea - Eco - Gov | Cli - Eco - Gov - Ene - CC - Cli |
| B7 | Dem - Ris - Hea - Dem | Cli - Hea - Eco - Gov - Ene - CC - Cli |
| B8 | Gov - Edu - Cul - Eco - Gov | Eco - Sec - Hea - Eco |
| B9 | Gov - H - Eco - Gov | |
| B10 | Gov - Env - Fun - H - Eco - Gov | |
| B11 | Gov - Edu - H - Eco - Gov | |
| B12 | Eco - Sec - Eco | |

Source: own elaboration.

On the one hand, the systemic articulation of urban elements such as government, economy, environment, education, health, and safety form positive, destabilizing loops (growing or decreasing), according to the internal management of the system. In favorable terms, these loops imply identifying synergies to achieve the proposed societal objectives efficiently and effectively. In negative terms, these loops may lead to collapse of the system.

On the other hand, urban elements such as disaster risk, population growth, culture, functionality, energy, and climate tend to create negative loops that stabilize the system by preventing or reducing its growth, since these elements depend on the evolution of external limiting factors, such as water and energy availability, among others. In this regard, climate variability and projections could reverse this relationship and cause the system to collapse if the city does not prepare or adopt mitigation and adaptation measures.

The causal diagram allows the identification of governance as the key element (the one that generates the most connections), the economy as the limiting element (the one that receives the most connections), and security as the inactive element (the one with the least connections) [54].

Recognizing the relationships between the external elements of the system, over which the system has no significant influence, and the internal elements, which the system can modify, is key to the goals set by the municipality, which imply major

territorial transformations and involve all the urban components, including the community, in order to achieve the proposed goals in an efficient and effective manner.

CONCLUSIONS

This study identified the influences and dependencies of 12 urban elements for the municipality of Pasto through the establishment of a system of 12 positive and 8 negative causal loops, with governance as the key regulatory element and the economy as the limiting element of resource availability under a changing climate. These loops show the importance of the city in articulating all its urban elements to generate synergies that foster its resiliency, rather than facing the possibility of destabilizing the system to its collapse.

Climate change has negative effects on the urban system related to agricultural losses, decreased food security, and water availability, as well as an increase in natural disasters (floods, landslides, and forest fires) and some public health diseases, which together can lead to social and economic destabilization of the community.

However, organizing the territory according to the principles of systemic thinking will allow the transition from negative effects to territorial opportunities based on the implementation of climate change adaptation and mitigation models.

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