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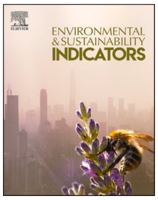

# Spatial neighborhood sustainability assessment for urban planning, Cuenca, Ecuador

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## ABSTRACT

The accelerated processes of urbanization produce an explosive occupation of the land, creating scattered cities, with great demands for infrastructure and high consumption of raw materials and energy, affecting natural territories and increasing the emission of pollutants. The city of Cuenca-Ecuador as well as several Latin American cities are not strangers to this problem, as it reflects a dispersed growth towards the peripheries that have caused an expansion of the urban landscape. The above situation requires sustainable planning, which contributes to decision-making to identify what measures are needed to regulate the growth of the city. Accordingly, the present research proposes combining the set of indicators of the Neighborhood Sustainability Assessment tool with the spatial analysis of GIS, so that the sustainability assessment can be extended at the city level to support urban planning in Cuenca. For this purpose, a 3-step methodology was proposed: selection of sustainable indicators, evaluation of sustainable performance, and design of a model that integrates SIG+NSA, which allowed incorporating spatial analysis in the sustainable assessment of neighborhoods, by designing a model adapted to Cuenca. This model consists of 15 variables, 12 indicators, and 4 evaluation categories, which result in the sustainable performance level of 149 planning sectors. The developed model makes it possible to automate the analysis processes and generate a complement to the ArcGIS geoprocessing tools for evaluating urban sustainability, as a support tool for planners and decision-makers in city planning processes.

## 1. Introduction

Currently, cities show a rapid urbanization process that puts pressure on the infrastructure and necessary resources to supply a growing population (UN-Habitat, 2016), which is manifested by the explosive land occupation, urbanization of territories that were destined for agriculture and natural reserves, the demand of large quantities of raw materials with their consequent pollution, among other impacts (Goldstein et al., 2013; The World Bank, 2022). This situation led countries worldwide to commit to changing their development model, guided by the principle of sustainability, which proposes a development that meets the needs of the present without compromising the ability of future generations to meet their own needs (Brundtland, 1987). Nevertheless, efforts to achieve sustainability have become critical with the arrival of COVID-19, especially in developing countries that have cities with poor urban zones and slums, where socioeconomic inequalities have increased (United Nations, 2020).

This is the situation of Cuenca, a city that is located in the Andes Mountain range in southern Ecuador. Despite having intermediate city characteristics (603,269 habitants (INEC, 2017)) that make it a locality with great opportunities for sustainable development additionally, it is one of the few cities in the country that is a good example of planning processes (UN-Habitat, 2015), it is not foreign to issues caused by rapid urban and population growth, access to housing in vulnerable sectors, the rise of land cost and the peri-urbanization phenomenon, have not been resolved and their consequences start to manifest in mobility, the rise of vehicle fleet and traffic (Municipality of Cuenca, 2019). For this reason, sustainable development of cities has ceased to be a long-term goal to become a necessary objective for guaranteeing a safer and more sustainable habitat (Kaizer, 2020).

The exposed problem demands the proposal of a new urban planning agenda that considers solutions to the urgent issues (Sharifi and Khavarian-Garmsir, 2020), and at the same time, it should generate new opportunities for a transition toward urban sustainability capable of

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tackling complexity and uncertainty (Madurai Elavarasan et al., 2021; Ranjbari et al., 2021). This overview makes urban planning become an essential tool for defining policies that could lead toward local sustainable development. Therefore, it is clearer that the information, particularly the quantitative indicators, and the sustainable assessment, play an important role in the decision-making to reach sustainable goals (Ameen et al., 2015; Hák et al., 2016). So, during the last decade, the use of sustainable indicators has become popular between public bodies and Decision Makers to identify the level of compliance with the proposed objectives (Rama et al., 2021). Internationally, a large variety of indicators have been defined, such as the Neighborhood Sustainability Assessment (NSA), tools that have developed groups of indicators that allow the sustainable performance evaluation of neighborhoods through international standards. Some NSA that stand out are LEED for Cities and Communities (U.S. Green Building Council, 2020), BREEAM Communities (BRE Global, 2012), and CASBEE for Cities (JSBC. Japan Sustainable Building Consortium, 2012), which despite being diverse in their scale, approach, and clientele, their common objective is to face the challenges related to global warming and urban sustainability (Sharifi et al., 2020).

NSA's evaluation systems have been broadly accepted as they are designed to educate about planning and policies' formulation guiding toward urban sustainability through the delivery of relevant data about the characteristics of urban systems. However, due to the large geographical area and regional variety, the international application of these tools has turned into an issue (Ameen and Mourshed, 2019; Boyle et al., 2018). On one hand, they have been highly criticized when intended to be applied to cities different from the ones they were created for, as their group of indicators does not respond to the needs and issues of each context (Kamble and Bahadure, 2020; Komeily and Srinivasan, 2015; Sharifi and Murayama, 2014). This becomes more evident between Global North and Global South countries since there are contextual differences as the developed countries' challenges are different from developing countries (Assefa et al., 2022). On the other hand, these tools are not spatial and are focused on a sole project evaluation, therefore by extending them to a larger scale (urban planning sectors), their evaluation systems turn insufficient (Pedro et al., 2018).

Despite this gap in the literature, it is still urgent the selection of an indicator system that addresses the priority sustainable needs of the city where they are going to be implemented while also aligning with the universal objectives of Sustainable Development (Musa et al., 2019; UNSD, 2015). For this reason, the city of Cuenca needs to define which NSA indicators address the priority needs of urban sustainability (European Commission, 2015; Komeily and Srinivasan, 2015; Merino-Saum et al., 2020; Sharifi and Murayama, 2014) and how to extend to a spatial level the assessment of urban zones, to identify their contributions to the city's overall sustainability (Pedro et al., 2019).

For this purpose, the research presents the possibility of complementing the NSA tools with those of GIS to solve each other's weaknesses so they contribute to sustainable urban planning, which is considered a problem of spatial decision that requires selecting where and what type of measures to implement. To answer "where", Geographic Information Systems (GIS) has been broadly used in urban planning as support for managing geo-referenced data, however, it has limited capabilities to represent the "what", meaning that it is the selection and the priority of sustainable indicators (Malczewski and Rinner, 2015). In this sense, the fundamental contribution of this study lies in determining the procedural aspect that allows a successful combination of the GIS with NSA, in addition to its representation through a model adapted to the city of Cuenca-Ecuador. For this study, a local NSA has been considered in order to expand the scale of evaluation of its indicators from neighborhood to city, through the incorporation of GIS spatial analysis using the Spatial Decision Support System (SDSS), which consists of interactive systems intended to assist the users in the analysis, planning, and decision-making through computerized processes that provide a setting for the adoption of rational decisions about different specific issues (Keenan and Jankowski, 2019).

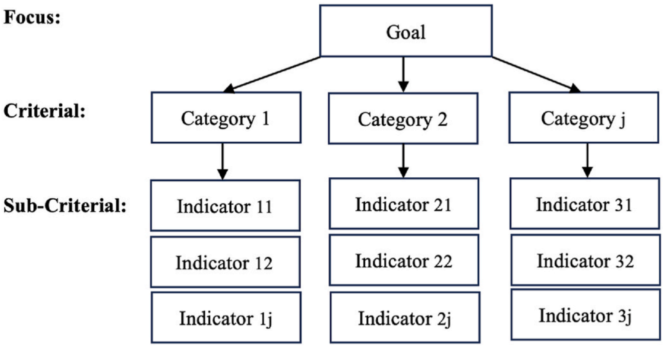

**Fig. 1.** Hierarchical structure proposed for the research.

## 2. Literature review

### 2.1. NSA (neighborhood sustainability assessment) tools

The NSA are evaluation tools that provide guidelines for the inclusion of measurements of sustainability into the development of neighborhood projects. They are systems constituted as multi-criteria models, hierarchically structured by categories, indicators, and scores, that allow through comparisons, the measurement of relations between the different categories and indicators, as well as weighting each model by level of importance (Sharifi et al., 2021). They incorporate a grading system that is structured by indicators that issue scores based on the compliance level which is multiplied by the mentioned weightings to obtain a global qualification for the certified neighborhood. Two fundamental aspects of the NSA are the indicators and the weightings. The indicators are measurements that allow for the quantification of the neighborhood sustainability and facilitate the decision making which can be based on better information and evidence. Whilst the weightings reflect the weight and importance that a NSA assigns to the topics or indicators depending on the local necessities, priorities or characteristics (Sharifi, 2021).

Studies about the development of the NSA have presented that few are the ones that dominate internationally, either for being the pioneers or due to their influence in the development of new tools. These are: LEED-ND, BREEAM Communities and CASBBE-UD (Braulio-Gonzalo et al., 2015; Kamble and Bahadure, 2020; Vilela et al., 2020). These NSA, on each update, have become less prescriptive, more flexible and transparent, which has allowed for easier selection of the indicators and the weightings adjustment (Pedro et al., 2019). Given these advantages, several adaptations of NSA have been developed around the world (Ameen and Mourshed, 2019; Braulio-Gonzalo et al., 2015; Dawodu et al., 2018; Ferwati et al., 2019; Matar et al., 2023), with the goal of easier recognition of particularities for the assessment of local contexts, which is fundamental for Global South countries that do not possess the

**Table 1**
Fundamental scale of AHP weighting (Saaty, 1987).

| Scale | Degree of importance | Explanation |
|---|---|---|
| 1 | Equal importance. | Two activities contribute equally to the objective. |
| 3 | Moderate importance of one over another. | The experience and judgment are in favor of an element above another one. |
| 5 | Essential or strong importance. | One element is strongly favored. |
| 7 | Very strong importance. | One element is very dominant. |
| 9 | Extreme importance. | One element is favored by at least a magnitude order of difference. |
| 2,4,6,8 | Intermediate values between the two adjacent judgments. | Use for finer graduation of judgment. |

same necessities or priorities as Global North countries (Dawodu et al., 2017; Tam et al., 2018).

### 2.2. Analytic Hierarchy Process (AHP) method

The method is used to solve complex problems that lack objectivity and need to define importance weightings to the elements that form the problem or are related to it. The problematic needs to be transformed into elements that integrate a hierarchically leveled structure (goal, criteria and sub-criteria) allowing to identify interrelations between the elements (see Fig. 1). The AHP method asks for a paired comparison between elements that constitute each level of the structure, through valuations in a numbered scale between 1 and 9 points (see Table 1), according to the contributions that each element gives to the upper level element which is being linked to or to the global objective (Saaty, 1987).

The alternatives (elements) paired comparison is the method's essence and is performed by an expert panel, which generally is the group of knowledge actors that possess experience about the problem. The method searches for consensus, and with the issued valuations by the experts (quantitative data) a matrix can be built which represents the relative priority between two elements (categories or indicators). The matrix with this property is designated reciprocal matrix "R" and it is represented as it follows:

$$R = \begin{matrix} 1 & r_{12} & \rightarrow & r_{1n} \\ r_{21} & 1 & \rightarrow & r_{2n} \\ \downarrow & \downarrow & \searrow & \downarrow \\ r_{1n} & r_{2n} & \rightarrow & 1 \end{matrix} \qquad [1]$$

The weightings are established by using the mathematical concepts of eigenvalue and eigen-vector. To estimate the weights vector (eigenvector) the following procedure was performed:

- Obtain the normalized matrix ($R_{Norm}$):

$$R_{Norm} = \left[ r_{ijNorm} = \frac{r_{ij}}{\sum_{i=1}^{n} r_{ij}} \right] \qquad [2]$$

- Estimate the weighting vector (w):

$$\widehat{w} = \left[ \widehat{w}_1 = \frac{1}{n} \sum_{j=1}^{n} r_{1jNorm}, \widehat{w}_2 = \frac{1}{n} \sum_{j=1}^{n} r_{2jNorm}, \ldots., \widehat{w}_i = \frac{1}{n} \sum_{j=1}^{n} r_{ijNorm}, \ldots., \widehat{w}_n = \frac{1}{n} \sum_{j=1}^{n} r_{njNorm} \right] \qquad [3]$$

In order to avoid inconsistencies and to make reliable weightings it is necessary to measure the consistency grade of the valuations issued by the experts. The measurement is made by the consistency index (CR) which determines the inconsistency level of the valuations and what Saaty (1990) suggests $CR > 0.1$ as unacceptable.

This AHP method has been very useful for the development of local NSA through the definition of weightings for the indicators that constitute the tool. For example, the development of an NSA that considers Irak's urban sustainability needs and priorities (Ameen and Mourshed, 2019). Other examples using the AHP method can be seen on researches performed for Qatar Sustainability Assessment System (QSAS) – Neighborhood Development (ND) (Ferwati et al., 2019) and Sustainable Urban Development (SUD), which identified the most relevant indicators for Iran (Amoushahi et al., 2022).

### 2.3. GIS (Geographic Information Systems) and SDSS methods

The spatial analysis is fundamental for the evaluation of urban sustainability given that the evaluation is modeled using a group of indicators based on the space for map production (Khodakarami et al., 2023). Nowadays, different methods of spatial analysis with Geographical Information Systems (GIS) are used to explore urban situations of interest (Saleem et al., 2020), among which is the Spatial Decision Support System (SDSS). These SDSS combine spatial data, GIS analysis functions and visualization, and decision models to facilitate the evaluation of problem solving through specific procedures in GIS that adapt to the characteristics and necessities of each particular problem (Pignatelli et al., 2023). The decision problems in SDSS are generally a combination of spatial and non spatial aspects that need geographical localization and their spatial relations (Keenan and Jankowski, 2019), therefore, their application for the evaluation of urban sustainability implies a combination of specific property data that measures indicators and spatial relations of the evaluated area.

In the field of urban sustainability evaluation, the SDSS have been developed thanks that GIS software (such as ArcGIS and open source ones) have gained a broad range of tools for analyzing and geoprocessing which facilitate the interaction with other softwares, expanding greatly the construction of spatial models for its evaluation (Steiniger and Hunter, 2013; Zhao et al., 2021). In this regard, there are studies that propose two SDSS that integrate GIS with LEED-ND (Pedro et al., 2018), and GIS with BREEAM-CM (Pedro et al., 2019) in order to identify the main areas and parameters of intervention within the framework for the Evaluation of the Urban Sustainable Performance of Lisbon.

### 2.4. GIS spatial analysis tools

For the development of SDSS, several GIS spatial analysis tools are combined, such as statistics for cluster analysis and weighted sum.

#### 2.4.1. Getis-Ord Gi*

It is a spatial grouping method (cluster), also known as urban conglomerates analysis, which classifies the objects creating groups or conglomerates as much homogeneous as possible within each group, and as much heterogeneous as possible between groups. The ArcGIS software provides the Getis-Ord Gi* tool, which through an equation, applies techniques to identify the locations of existing clusters, marking hot spots (high values) and cold spots (low values). The equation is as it follows (ESRI, 2015a):

$$G_i^*(d) = \frac{\Sigma_j W_{ij}(d) X_j}{\Sigma_j X_j} \qquad [4]$$

$G_i$*(d) = is the indicator of local autocorrelation calculated for (i) entity at a (d) distance.
$X_j$ = is the value of each (j) entity's attribute.
$W_{ij}$ = is the spatial weight between (i) and (j).

The Getis-Ord Gi* tool returns, for each entity of the data cluster, a z

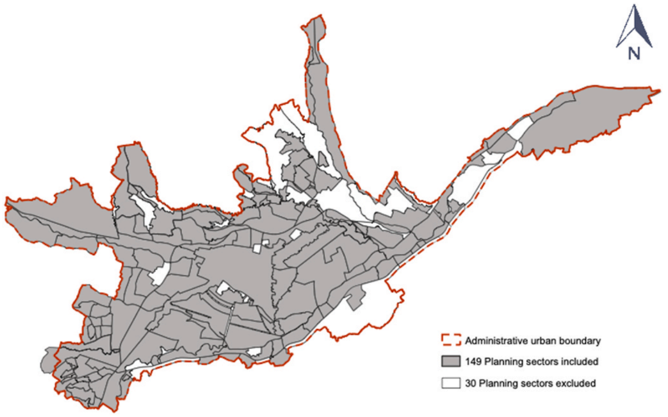

**Fig. 2.** The urban zone of Cuenca-Ecuador and planning sectors.

score (standard deviation), a p value (statistical probabilities), and a trust level Gi_Bin (90%, 95%, 99%). The value p and z scores are measurements of statistical significance and are associated with a standard normal distribution. The z score indicates that, when it's too low or high and it's associated with very small p values, it is highly unlikely that the spatial pattern is random, making it possible to reject the null hypothesis (randomness). The p value indicates, when it is too small, that it's very unlikely that the spatial pattern is the result of randomness (ESRI, 2015b). The trust level Gi_Bin identifies hot spots (positive values) and cold spots (negative values) statistically significant in a 7 level scale (−3, −2, −1, 0, 1, 2, 3). The entities in bins of +/−3 values reflect a trust level of 99%, bins of +/−2 values represent 95%, bins of +/−1 equals 90% and a bin of 0 is not statistically significant (ESRI, 2015b).

As discussed, this analysis technique allows to identify specific cluster locations on different types of variables, for which, few urban studies have been used, as the one on Pedro et al. (2019), which through Getis-Ord Gi*, anages to classify Lisbon's subsections according to their level of sustainable performance.

### 2.4.2. *Weighted sum*

The weighted sum tool provides the possibility of adding weights and combining various entries to create an integrated analysis. It consists of two steps: Firstly, multiplication of the selected field values for each input raster by a specified weight, and secondly, addition of all these input rasters to create an output raster.

This tool is similar to the weighted overlay, but it differs in that weighted sum supports more types of field data (integer and floating point values) and does not rescale the resulting values into a new evaluation scale, therefore the analysis maintains its resolution. Additionally, the weighting values can be any positive or negative decimal value, and do not need to be restricted or equal to 1.0 (ESRI, 2016).

The characteristics of this tool have allowed it to perform different applications in various multicriteria researches, as weights can be assigned to the required number of variables based on the importance level in the analysis. For this reason, these tools are used in conjunction with multicriteria analysis techniques such as AHP, which can determine weights for each variable by generating a consensus with the results given by the experts. The equation used for calculating is as follows:

$$GSS = \sum_{i=1}^{n} \left[ \left( \frac{100 * P_i}{7} \right) * W_i \right] \tag{5}$$

GSS = is the score of global sustainability (0–100%)
Pi = is the level of each variable's performance
Wi = is the assigned weight for each variable (1–100%).

## 3. Materials and methods

### 3.1. *Area of study*

The area it's defined as the urban zone of the city of Cuenca-Ecuador, south of the Ecuadorian mountain range with a surface of 73,79 km2, approximately located at 2° 53′ 51″ S y 79° 00′ 16″ O coordinates according to its centroid, with an average altitude of 2550 m s.n.m. For this study, for the analysis units it has been considered the city's "planning sectors", which are established in the "Land Use Planning for the City of

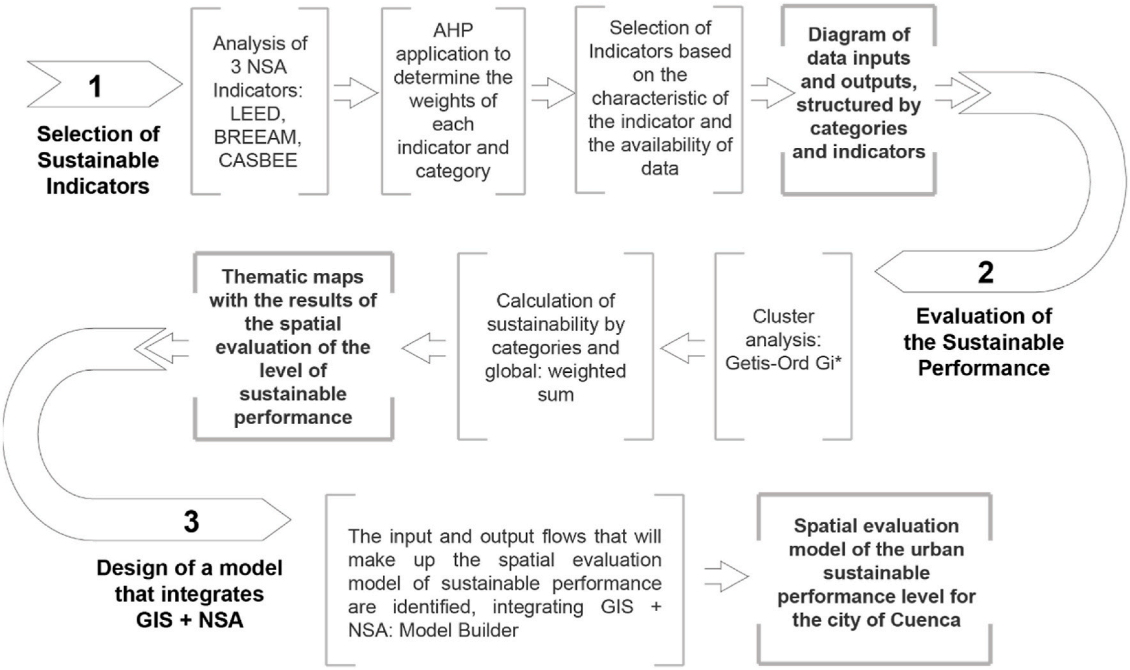

**Fig. 3.** Methodology's diagram.

**Table 2**
Panel of experts composition.

| Expert group | Participants | | Distribution |
|---|---|---|---|
| | # | % | |
| Academia | 15 | 20% | Professional = 6.7%<br>Master = 73.3%<br>Ph.D. = 20% |
| Government officials | 20 | 26,70% | Professional = 65%<br>Master = 35% |
| Private professionals | 40 | 53,30% | Professional = 37.5%<br>Master = 62.5% |

Cuenca". These sectors constitute the official geographical and urban units for the city's planning and are defined based on the identification of homogeneous physical and spatial land characteristics which can be of geomorphological, environmental, landscape, urban, socio-economic, historical-cultural, among other types. In total, there are 179 planning sectors (Municipality of Cuenca, 2003). Thirty sectors have been excluded as they do not possess building permits nor built projects. These can be for forestry use, geological instability, flood risk areas, high impact industries, and special sectors that correspond to military bases, oxidation ponds and university premises. For this reason, only 149 planning sectors were analyzed in this study (Fig. 2).

## 3.2. Methodology

The methodology process is developed in 3 steps (Fig. 3).

### 3.2.1. First-step: selection of sustainable indicators

For the study, based on the literature review three NSA were selected: BREEAM Communities, LEED-ND, and CASBEE-UD. These three tools were chosen because several authors have established that these are the most internationally recognized NSA, with a large number of certified urban projects and their information, including their assessment methodologies and scores, is open access (Ferwati et al., 2019; Kaur and Garg, 2019; Sharifi et al., 2021; Sharifi and Murayama, 2015).

The three NSA's 141 indicators were analyzed in order to identify the ones that are repeated and can be standardized, additionally to each indicator's potential to be applied to the study context based on the availability of information required for their evaluation. Furthermore, the components of each indicator were analyzed as well, such as objectives, evaluation method, measurement units, score assignment, and weighting (Quesada-Molina and Astudillo-Cordero, 2023). The information required by the indicators was collected from different sources, including websites of institutions responsible for providing services to the local population, official reports of diagnosis about required topics, interviews with municipal officials and urban promoters, perception surveys to its habitants, and gathering on-site data.

For the selection of indicators, two criteria have been considered: data availability and the indicator's characteristics (if the indicator possesses a prescriptive or performance focus). In order to evaluate urban sustainability in cities, the availability of data has become crucial (Cohen, 2017; Matar et al., 2023), due to the existing institutional restrictions for data access or the lack of data in public institutions. A performance indicator focuses on the result, whilst a prescriptive indicator focuses on the process and provides a guideline for the evaluation step by step. The research ruled out the prescriptive indicators since they propose procedures (step by step) for the evaluation, which require detailed information that is not possible to acquire to its level of resolution or is not available. For instance, the indicator titled "Community participation" requires 4 steps: 1. Make a consultation plan, 2. Do a workshop with the community, 3. Integrate the proposed changes, and 4. Do another workshop to socialize the reforms. This prescriptive focus might be adequate for a neighborhood scale but is not feasible for a larger scale as the information is not available. Therefore, only indicators with performance characteristics that can be applied to city scale and availability or data access were analyzed (Pedro et al., 2019).

#### 3.2.1.1. Defining weights.

To define the importance weights of evaluation criteria, the consensus of experts was chosen using the Analytic Hierarchy Process (AHP) method.

The AHP method was developed by R. W. Saaty (1987) and to date, it has been used to derive importance weights for situations involving consideration of multiple criteria (Ajibade et al., 2019). The method consults a panel of experts about comparison alternatives through the interpretation of data in a hierarchical structure. At each level of its hierarchy, comparisons are made between pairs of elements based on the contributions of importance that each one of the compared elements makes to its higher level. The comparisons are evaluated according to the numerical scale that the method provides (1–9). Finally, the contributions of each alternative to the overall objective are calculated through additive aggregation.

For the application of the AHP method, a structured questionnaire survey was designed and sent by email and it consists of forced-choice questions to collect quantitative data. The questionnaire posed questions with the comparison of two aspects through which experts must assign a score on a scale of 1–9. The experts' panel, shown in Table 2, was established with 75 highly informed on the planning of Cuenca professionals, academia, public officials, and private professionals, as suggested by Alyami and Rezgui (2012).

### 3.2.2. Second-step: evaluation of sustainable performance

In this step, it was necessary to first determine an evaluation methodology that could be adjusted to the requirements established in the demands and standards that each indicator requires to meet. Each requirement was assigned a variable to distinguish its respective evaluation criteria, which later constituted the information inputs of the flowchart. The approach of evaluation of the indicator's variables is binary, which means that their compliance is based on a nominal scale between "Yes" and "No". For this reason, the proposed evaluation criteria for each variable were also expressed by that denomination. Therefore, under the "Yes" are presented standards that if reached will demonstrate that the planning sector meets the requirements of the indicator, whilst under "No" are the standards that if they are reached will demonstrate that the planning sector does not comply with the indicator's requirements. The indicators with their variables, methods, and evaluation criteria are shown in Appendix A.

The assignment of the requirements of the variables to the "Yes" and "No" sections, prevents confusion in the scales of evaluation because the high or low values on variables do not necessarily equate to a high or low level of sustainable performance. For instance, the V4 variable of density, to a higher value of density a better level of the sector's performance will be, reflecting a positive trend. However, the V1 variable which is about the number of areas where construction is prohibited, the lower the value of areas a better level of the sector's performance will be, which reflects a negative trend.

Following the methodology found by Pedro et al. (2018), to the terms "Yes" and "No", a value of 2 and 0 were assigned respectively. Meanwhile, the values between these two numbers were located in a third scale named "Maybe", which will collect all those possible options that fall out of the "Yes" and "No" standards and were also assigned a value of 1.

A summary table is elaborated as a partial result of this phase, showing the results obtained in the evaluation of each variable (maximum, minimum, and average value) in the 149 analyzed planning sectors.

#### 3.2.2.1. Cluster analysis: Getis-Ord Gi*.

Once the evaluation of each indicator was completed, the next step was to identify to what extent the planning sectors meet the indicators' requirements, meaning that it was determined how far or how close each sector was to achieving a "Yes" or a "No". In this sense, an interval scale was proposed to capture the existing values in the distance between the "Yes" and "No" standards. This calculation was performed using statistical tools for cluster analysis. It was proposed the use of the local technique Getis-Ord G*, since it allows the identification of urban patterns and spatial autocorrelation by distinguishing hot and cold spots. This was done using the Hot Spot Analysis tool, which is part of the toolbox of ArcGIS Pro by Esri versión 3.0.

Afterwards, a conversion of the levels was performed for each variable so they correspond to the same 7 level scale (1, 2, 3, 4, 5, 6, 7), where 1 represents the sectors with the lowest level and 7 represents the sectors with the highest level of sustainable performance. As a result of this stage, 12 maps were developed showing the results of the evaluation of the sustainable performance level of the planning sectors, which correspond to the 12 selected sustainability indicators. These maps are presented in the Results section.

*3.2.2.2. Categorically and globally calculation of sustainability: weighted sum.* Regarding the evaluation of the level of sustainable performance by categories and global, this latter is considering the city as a whole, the performance score of the planning sectors was estimated based on the calculation of the Weighted Sum of the analyzed indicators applying the [5] formula.

As a result of this stage, 5 additional maps were elaborated with the results of the sustainable performance evaluation of the planning sectors. These correspond to the 4 evaluation categories (E= Ecology, Land Use and Occupation, I= Infrastructure, T= Transportation and Mobility, A= Neighborhood Environment) and 1 of the global performance of the urban area of the city. These maps are shown in the Results section.

### 3.2.3. Third-step; design of a model that integrates GIS + NSA

Based on the processes carried out, and with the support of GIS tools, a Model of Urban Sustainable Performance Evaluation was proposed, which contains the workflow that links the used sequences of geoprocessing tools. These workflows allow the integration of the spatial analysis of GIS with sustainable indicators.

The GIS+NSA model was developed using the ArcGIS Pro ModelBuilder tool, which through a visual programming language allows explaining effectively the processes that must be followed to apply the model. The structure of the designed Model considered 6 yellow colored steps (inputs) with their respective green colored layer results (output), for the evaluation of each indicator. A seventh step was added for the evaluation of categories and an eighth one for the global evaluation. As a preliminary step (input layer), the variables evaluation's results (V1–V15) which are the input data of the model, were considered as follows:

1. A new field was added to the table of the input layer for each indicator, and they are denominated by the indicator's code (I1–I12).
2. Each indicator was evaluated on the ArcGIS Pro field calculator using a Python language expression that considers its specific evaluation criteria. These criteria correspond to those exposed in the Evaluation Criteria column of Appendix A.
3. With the result of the evaluated indicator, a hot spot analysis was carried out using the Getis-Ord Gi* tool, from which a layer with a scale of −3, −2, −1, 0, 1, 2, is obtained.
4. In the resulting layer, a new field was added under the GiBin-Reclass denomination, which will keep the re-classified values.
5. A calculation in the field GiBin_Reclass was made using a Python language expression, to re-classify the results into the 1–7 scale, where 1 represents the lowest level of sustainable performance and 7 stands as the highest level. From this step, 12 maps are obtained and

**Table 3**
Selected indicators by categories.

| Category | Weighting | Indicator | Normalized Weighting |
|---|---|---|---|
| Ecology, land use and occupation | 22,2% | Ecology and conservation | 13,10% |
| | | Slope and landform protection | 12,05% |
| | | Land use | 11,88% |
| | | Land protection | 11,51% |
| | | Ecological value quality | 11,12% |
| | | Evaluation of flood risk | 10,19% |
| | | Natural landscape | 8,53% |
| | | Mixed use of land | 7,82% |
| | | Housing sustainable certification | 7,11% |
| | | Local context harmony | 6,69% |
| | | Sum by category | 100% |
| Infrastructure and Equipment | 20,3% | Access to basic infrastructure | 20,28% |
| | | Capacity of answer to disasters | 19,44% |
| | | Access to public equipment | 12,11% |
| | | Residential garbage management | 11,10% |
| | | Construction disposal management | 9,76% |
| | | Historical infrastructure preservation | 9,65% |
| | | Inclusive design | 9,40% |
| | | Re-used and recycled infrastructure | 8,26% |
| | | Sum by category | 100% |
| Transportation and Mobility | 17,9% | Transportation CO2 emissions | 24,16% |
| | | Access to public transportation | 23,71% |
| | | Vehicle and pedestrian traffic | 19,12% |
| | | Public transportation installations | 16,90% |
| | | Bicycle installations | 16,11% |
| | | Sum by category | 100% |
| Resources and Energy | 15,6% | Reduction of water consumption | 22,99% |
| | | Sewage management | 20,52% |
| | | Rainwater management | 16,21% |
| | | Energy strategy | 15,01% |
| | | Optimization of energetic performance | 13,96% |
| | | Low-impact materials | 11,31% |
| | | Sum by category | 100% |
| Participation and Social well-being | 14,4% | Social housing provision | 44,15% |
| | | Community participation | 32,38% |
| | | Neighborhood management | 23,47% |
| | | Sum by category | 100% |
| Neighborhood Environment | 9,6% | Heat island effect | 40,01% |
| | | Noise pollution | 35,63% |
| | | Light pollution | 24,36% |
| | | Sum by category | 100% |
| Total sum | 100% | | |

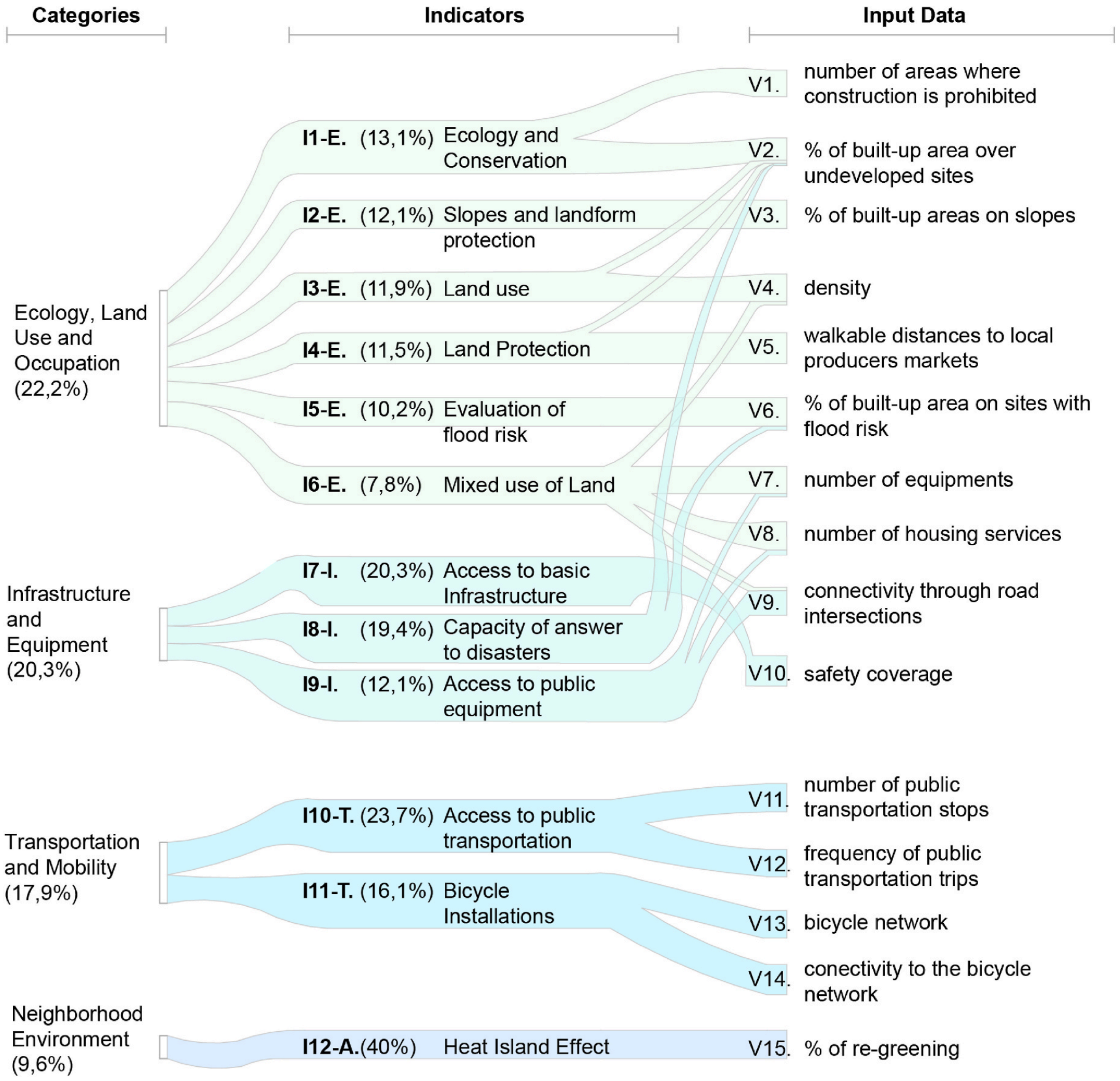

**Fig. 4.** Diagram of data input and output. Source: Prepared by the author.

they show the results of the evaluation of the level of sustainable performance per indicator.

6. The resulting layers were converted to raster so that the following calculation can be performed since the weighted sum accepts only raster layers.
7. The Weighted Sum calculation was performed using the weights that the NSA provides for each indicator, whereby 4 additional maps were obtained with the results of the evaluation of the level of sustainable performance for each category.
8. Finally, the Weighted Sum calculation was performed again, using the weights that the NSA exposes for each category to obtain a map showing the results for the global evaluation.

As a result of this stage, a model of evaluation of the level of urban sustainable performance adapted to the city of Cuenca was designed.

## 4. Results

### *4.1. Sustainable indicators and weights*

From the NSA indicators analysis, it resulted in 35 indicators grouped into 6 categories: 1. Ecology, land use and occupation, 2. Infrastructure and Equipment, 3. Transport and Mobility, 4. Resources and Energy, 5. Participation and Social well-being, 6. Neighborhood Environment. With this hierarchical structure, the panel of experts was consulted to provide the weighting for each indicator and category (Table 3).

Once these 35 indicators were identified, only 12 of them showed performance characteristics and could be scaled to city levels with data availability, which represents 36.26% of the total weighting assigned by the panel of experts to the 35 indicators. These twelve indicators were selected for their descriptive characteristics, meaning that they focus on the result and do not require detailed information, due to the planning sector's large scale it can be difficult to find information with a great level of detail. Additionally, data access is problematic in several cities from Global South countries (Cohen, 2017), since in many cases, data does not exist nor is up to date. Therefore, twelve indicators were selected and grouped into four categories, and were assigned variables based on established requirements by their evaluation methodologies resulting in the following diagram of inputs and outputs, which is structured by categories and indicators. The elaborated diagram (Fig. 4) contains 15 variables (V1–V15) for 12 indicators (I1–I12) with their weights and grouped into 4 categories. For instance, within "Ecology, Land use and Occupation" category, the I1-E indicator of ecology and

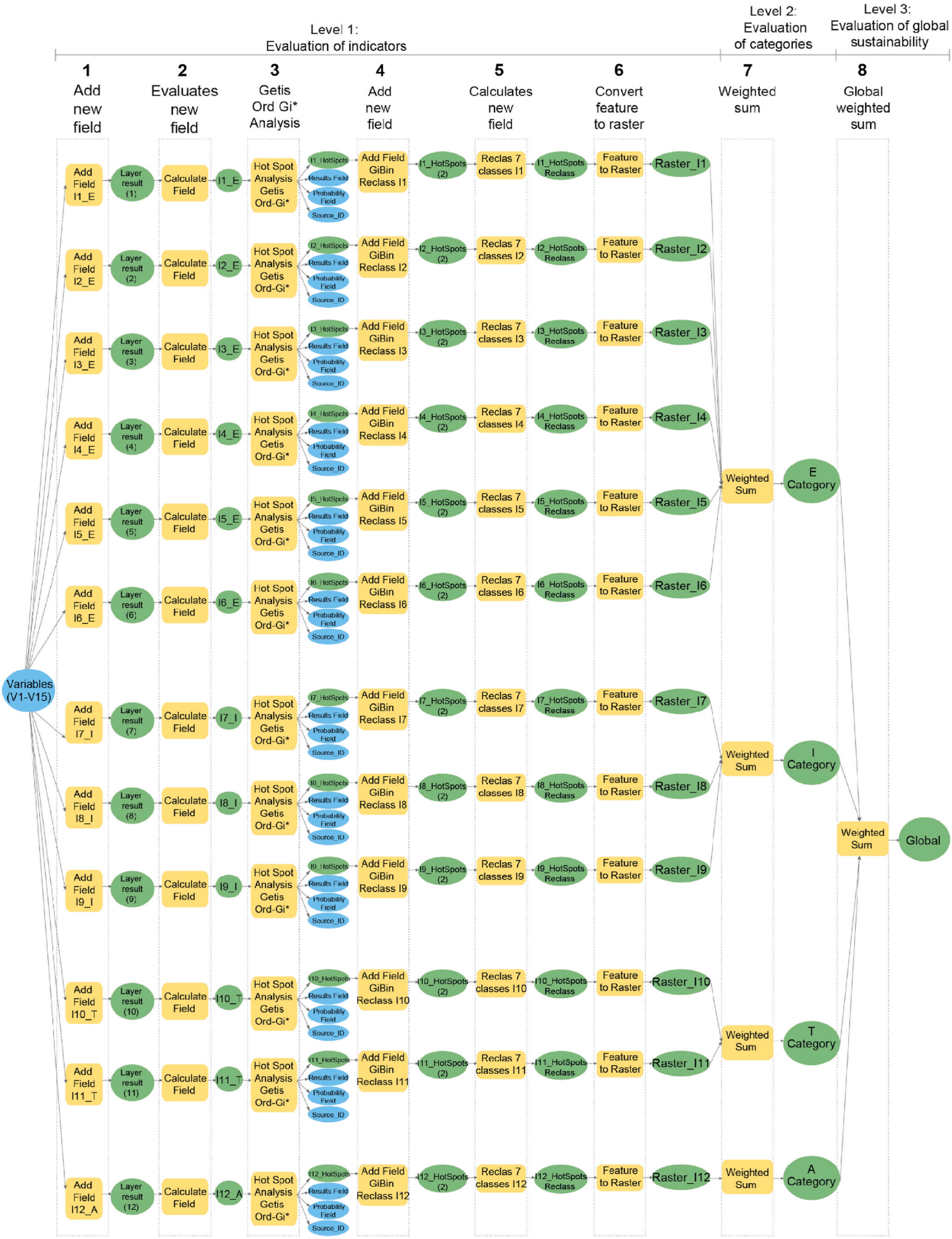

**Fig. 5.** Model of the evaluation of urban sustainable performance for Cuenca. Source: Prepared by the author.

**Table 4**
Results obtained from the evaluation of each variable. Source: Prepared by the author.

| Variables | Variable Code | | Unit | Min. | Max. | Avg. |
|---|---|---|---|---|---|---|
| Number of areas where construction is prohibited | V1 | | u | 0 | 0 | 0 |
| Percentage of built-up area on undeveloped sites | V2 | | % | 0 | 148 | 7,75 |
| Percentage of built-up areas on slopes | V3 | | % | 0 | 7 | 0,33 |
| Density | V4 | | Dwellings/Ha | 1,50 | 77,15 | 17,21 |
| Walkable distance to local produce markets | V5 | | m | 249,91 | 21414,71 | 6384,85 |
| % of built-up area on sites with flood risk | V6 | | % | 0 | 41 | 3,57 |
| Number of urban equipment | V7 | | u | 2 | 466 | 43,51 |
| Number of housing-related services | V8 | | u | 0 | 767 | 22,24 |
| Connectivity by road intersections | V9 | | u/km2 | 0 | 500 | 148,09 |
| Security coverage | V10 | | u/km2 | 0 | 3 | 0,42 |
| Number of public transport stops | V11 | | u | 0 | 317 | 27,14 |
| Frequency of public transport trips | V12 | | min | 5 | 20 | 8,41 |
| Bicycle network | V13 | | u | 0 | 15 | 1,44 |
| Connectivity of the bicycle network | V14 | V14_E | u schools | 0 | 30 | 5,23 |
| | | V14_P | u stops | 0 | 55 | 15,39 |
| | | V14_S | u services | 0 | 119 | 17,04 |
| % of re-greening | V15 | | % | 0 | 65 | 8,01 |

conservation requires the evaluation of variable 1 (V1) which is the calculation of the number of areas where construction is prohibited, and variable 2 (V2) which is the percentage of the built-up area over undeveloped sites.

The variables constitute the available input data for the city of Cuenca at the level of the urban sector. This diagram served as the basis for the following evaluation of the planning sector's performance and the development of the Model adapted to Cuenca.

### 4.2. *Design of a model that integrates GIS + NSA*

As a result, a model of urban sustainable performance evaluation for the city of Cuenca was obtained, which contains the workflow (inputs and outputs) that integrates the spatial analysis of GIS with the sustainable indicators (Fig. 5). These workflows link the sequences of the geo-processing tools used (Getis Ord-Gi* and Weighted Sum). In level 1 the evaluation of indicators is performed (Steps 1–6), in level 2 is the evaluation of categories (Step 7), and in level 3 the evaluation of global sustainability is conducted (Step 8). The GIS+NSA Model was developed using the ArcGIS Pro ModelBuilder tool, through a visual programming language as shown in Fig. 5. The Python language script of the Model is presented in Appendix B.

### 4.3. *Evaluation of sustainable performance*

The designed model in 4.2 has been applied to the 149 planning sectors of Cuenca. Results for each planning sector were obtained from the carried-out evaluation based on the evaluation criteria described in Annex A. Table 4 represents the minimum, maximum, and average data determined in each variable's evaluation.

From level 1, which is the indicator's evaluation, it resulted in a map for each indicator making a total of 12 maps. These maps show the evaluation of the twelve indicators of the NSA tool. Although these indicators are not spatial in nature, when combined with GIS tools, they allow the visualization of spatial patterns for all 149 planning sectors based on their levels of sustainable performance. For instance, the resulting map of indicator I7–I (Fig. 6g) shows that sectors with lower access to basic infrastructure are located at the southwest and east sectors of the city, whereas the best performance levels are found in the central sectors. The visualization of urban patterns would not be possible with the evaluation of NSA'S indicators only, but rather requires the support of GIS spatial tools.

The planning sectors with the lowest and highest level of sustainable performance are symbolized using the 7 interval scale ranging from lowest to highest (1–7). This scale, provided by the Getis Ord-Gi* tool, was used as it allows to represent how close or far a sector is from achieving sustainable performance.

In level 2 the results from the categories evaluation with a map per category was obtained, totaling 4 maps (Fig. 7a b.c.d). These maps include the assigned weights for each indicator and allow visualizing where the evaluated sectors with lower or higher sustainable performance are grouped in relation to each category using the same 7-interval scale. For instance the T Category map is shown, where the sectors with higher access to transportation and mobility are located at the center, south and west sectors of the city, whereas towards the east and southwest outskirts of the city, the lower levels of performances are observed.

Finally, in level 3 was obtained a map with the results of the global sustainability evaluation, which includes the results of all indicators and categories with their respective weights, and it is presented using the 7-interval symbology (Fig. 8). The map shows the location of two planning sectors, N21–B at north and CH at the center, that correspond to the sectors with the lowest and highest sustainable performance in comparison to the rest of the city's planning sectors.

## 5. Discussion

The investigation adopts an SDSS method (Spatial Decision Support System) that allows the development of specific procedures that respond to the characteristics and needs of the investigation's problem. This way, the spatial analysis of GIS was integrated with a tool for assessing neighborhood sustainability and allowed the evaluation of Cuenca City. Nonetheless, some limitations were observed:

In regards to the definition of the analysis unit, we used planning sectors as they are the official urban units of Cuenca's urban plan. However, upon analysis, it became evident that these sectors differ in terms of size and shape, raising concerns about their homogeneity and yielding statistically insignificant results for various sectors. This observation should be considered in future research endeavors, with the aim of selecting more homogeneous units of analysis.

Other limitations such as data collection for the indicators evaluation, has also been expressed by previous similar investigations, in which it can be observed a low number of evaluated indicators due the limitations that NSA tools have, as they require detailed levels of data for the evaluation of many indicators which summed to the lack of data accessibility especially in Global South countries, influence in the results' spatial resolution. In comparison to previous studies, like the one in Pedro et al. (2018) for the city of Lisbon, 18 indicators and 25 variables were selected out of 40 indicators proposed by BREEAM's tool; or in Pedro et al. (2019) for the same city, only 10 indicators with 26 variables were selected out of 53 proposed by LEED's tool. In this study, for the city of Cuenca only 12 indicators with 15 variables out of the 35

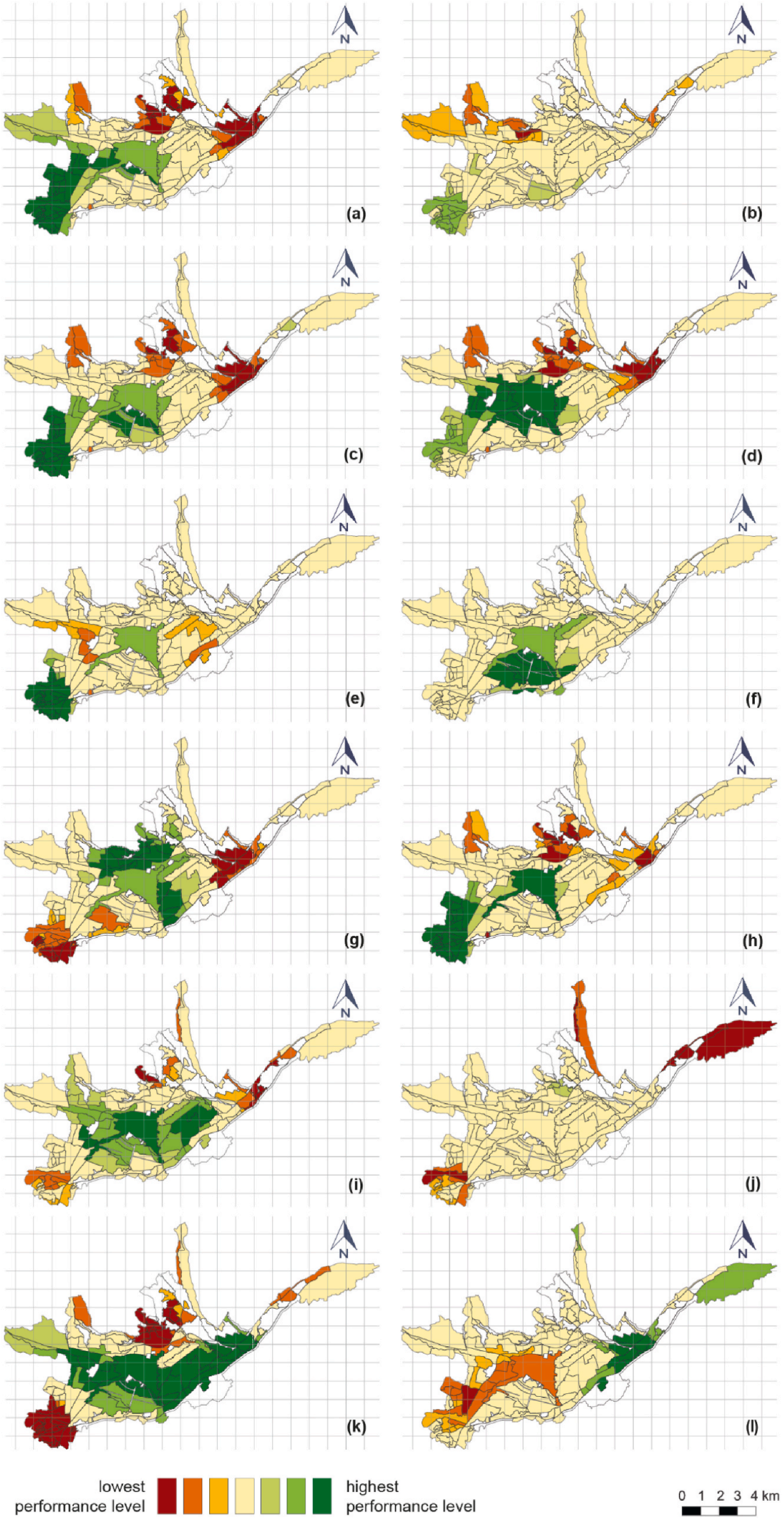

**Fig. 6.** Thematic maps with the results of the evaluation of indicators: (a) I1_E Ecology and conservation, (b) I2_E Slope protection, (c) I3_E Land use, (d) I4_E Land protection, (e) I5_E Evaluation of flood risk, (f) I6_E Mixed use of land, (g) I7_I Access to basic infrastructure, (h) I8_I Capacity of answer to disasters, (i) I9_I Access to public equipment, (j) I10_T Access to public transportation, (k) I11_T Bicycle installations, (l) I12_A Heat Island Effect. Source: Prepared by the author.

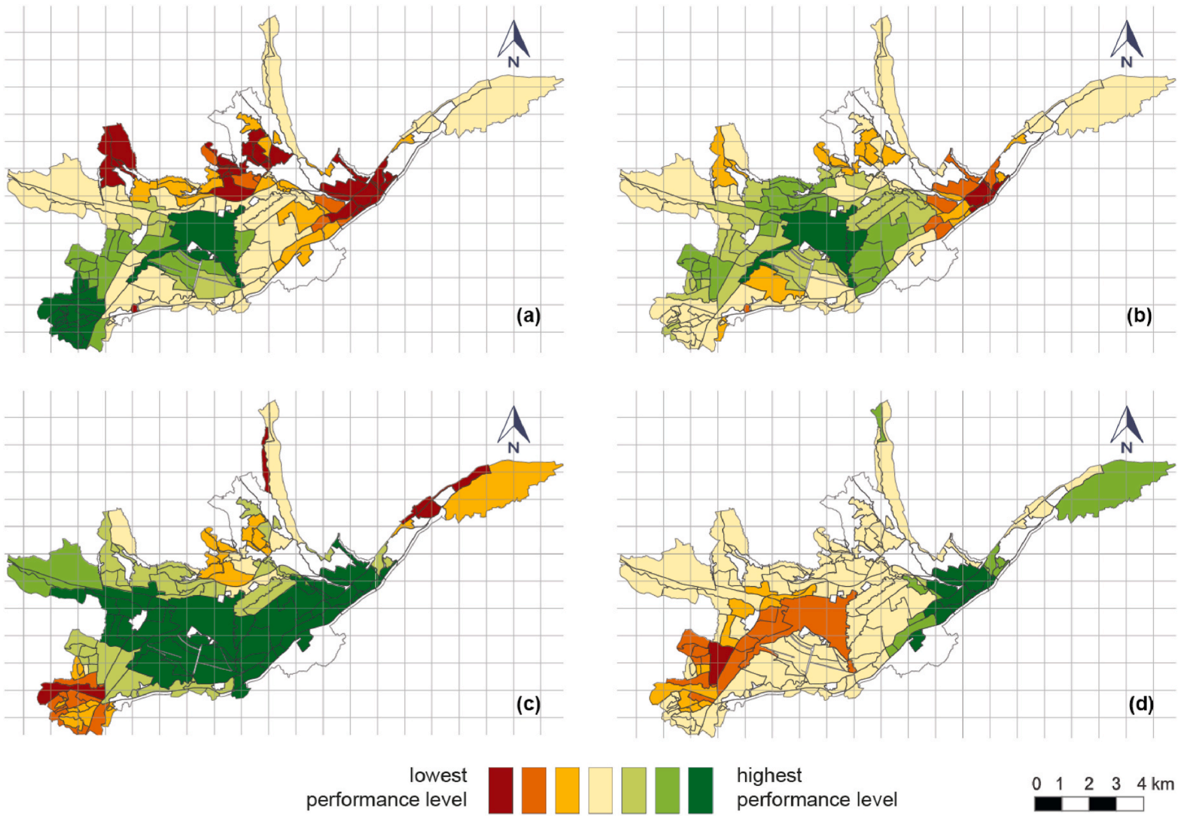

**Fig. 7.** Maps with the results of the evaluation by categories: (a) E Ecology, Land Uses and Occupation, (b) I Infrastructure and equipment, (c) T Transportation and Mobility, (d) A Neighborhood Environment. Prepared by the author.

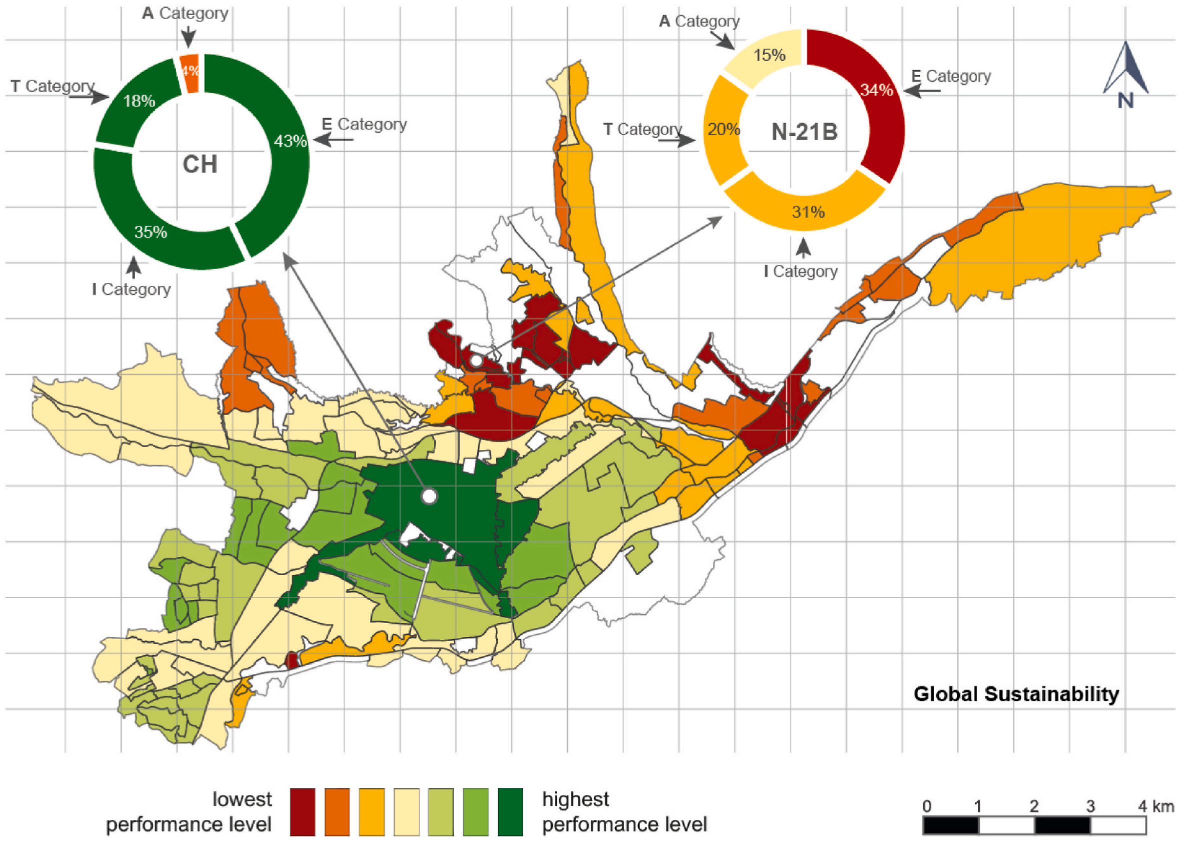

**Fig. 8.** Maps with the results of the evaluation of global sustainability. Prepared by the author.

proposed indicators by the local NSA were evaluated. As a result, there is a significant difference with the global sustainability score provided by the tool, as only 36.26% of the total weight could be evaluated.

The selection of 12 indicators with 15 variables (V1–V15), grouped into 4 categories (E= Ecology, Land Use and Occupation I= Infrastructure and equipment, T= Transport and mobility, A= Neighborhood environment) allowed the sustainability evaluation could be contextualized to the conditions of 149 planning sectors in the urban area of the city of Cuenca, and its weights correspond to the importance level that each indicator and category has for the city. The variables established the evaluation criteria or requirements for the fulfillment of each indicator and they are detailed in Appendix A. Moreover, a diagram of data inputs and outputs was obtained based on the requirements that the indicators establish (Fig. 4). This allowed the identification of priority sectors as well as specific sustainability topics needed by each one.

Regarding spatial analysis, a series of GIS software tools were of great help for managing the raster and vector formats, as well as databases that made it possible to evaluate sustainable variables and indicators. Additionally, GIS aptitude for managing large data volumes enabled the performance of various calculations in all the planning sectors of the urban zone of Cuenca. Thus, it was possible to observe that the GIS' spatial analysis constituted a great utility tool for the evaluation of the city's sustainability and it can contribute to urban planning processes as has been stated in other investigations (Alshuwaikhat and Aina, 2006; Rojas Quezada et al., 2008).

Fig. 6 shows the specific evaluation of each one of the 12 evaluated indicators. The results contribute to identifying which specific urban policies need to be applied and which planning sectors are a priority. For example, regarding the slope protection indicator (I2_E), urban policies can be focused on the sectors of the northwest of the city, through an improvement in urban control in those areas to avoid construction that may show problems due to landslides in the future. In the case of the land use indicator (I3_E), public policies could focus on increasing density in some specific sectors in the north and east part of the city. Regarding the access to basic security infrastructure indicator (I7_I), public policies can be focused on providing new Community Police Units (UPC) in the southwestern and eastern sectors of the city. Similarly, regarding the access to public transportation indicator (I10-T), urban policies can be proposed such as reducing travel frequencies in sectors located at the eastern and southwestern limits of the city.

Fig. 7 (a.b.c.d) shows the evaluation of the 12 indicators grouped by categories through a weighted sum. Four maps are displayed, in which the planning sectors with higher or lower performance levels can be seen in each of the categories: E, Ecology, Land Use and Occupation; I, Infrastructure and equipment; T, Transportation and mobility; and A, Neighborhood environment. Category A was observed as the one that obtained the lowest levels of performance. Additionally, Fig. 8 shows a map with the results of the overall evaluation, determined through the application of a second weighted sum with categories E, I, T, and A, and their respective weights. The resulting map reflects a summary of the total evaluation, where it was observed that the sector with the lowest level of sustainable performance is located in the north of the city, with the code N–21B. The latter obtained a level 1 on performance in the category E, which corresponds to 34% of its evaluation; a level 3 in the categories I and T, corresponding to 51% of its evaluation, and a level 4 in the A category, corresponding to the remaining 15% of the evaluation.

On the other hand, the sector with the highest level of sustainable performance was CH. This sector obtained a level 7 in E, I, and T categories, representing 96% of its evaluation, and A was the only category where it obtained a level 2, representing 4% only of its total evaluation. Due to these scores, the sector obtained the best evaluation. Furthermore, it can generally be observed that the lowest levels of performance were mostly found in the sectors located at the northern and eastern boundaries of the city's urban profile, whilst the highest levels were found in CH and surrounding sectors, coinciding with what is stated in the literature that the best quality of life conditions are generally found in consolidated centers, while lower standards of quality of life are observed in the peripheries.

In regards to the proposed model, Fig. 5 presented the input and output flows that are necessary for the urban sustainable performance evaluation model that integrates GIS + NSA and is adapted to the local conditions of the city of Cuenca; the Python language script is also attached in Appendix B. The designed model it's structured with 6 inputs and 6 outputs that allow the evaluation and visualization of the results of each indicator. These results are grouped by categories and feed a seventh input, which returns the evaluations by categories, which in return feeds an eighth input, which delivers the evaluation of the overall sustainable performance of the city.

## 6. Conclusions

The results are an important contribution to support decision-making in urban planning in Cuenca city, given that effective policies on specific sectors can prevent situations and remedy others. Moreover, when applied in an intermediate city like Cuenca, these policies would help maintain more balanced and sustainable urban patterns in its growth process. The proposed model allows for the automation of the analysis processes and can be used as a plugin to ArcGIS geo-processing tools for evaluating the sustainability of Cuenca, this is as support for urban planners and decision-makers in city planning processes. The model can also be adapted to other contexts by replacing the weights according to the priorities and conditions of each site.

Finally, it was observed the feasibility of using multi-criteria tools such as local NSA for analyzing the sustainability of cities, as well as the spatial analysis of GIS in evaluating and managing large volumes of data, which allowed the development of an adjusted SDSS model that suits the characteristics and needs of the problem at hand. Similarly, GIS enabled the visualization of results through thematic maps that can inform the community and promote citizen participation in matters concerning the sustainable development of their city.

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## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

I have shared the data in Appendices A and B attached to the manuscript

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.indic.2023.100307.

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