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4D Model for Impact Analysis in Hydroelectric Projects

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Abstract – This study proposes a four-dimensional analysis model to assess the impacts generated by reservoir-based hydroelectric projects: multi-spatial, multi-temporal, multi-decision-maker, and multi-criteria. Rather than replacing existing Environmental Impact Assessment (EIA) methodologies, the model is designed to complement and enhance the EIA process. The research employs a combined methodology that includes a systematic literature review using PRISMA, impact relationship analysis through DEMATEL-WINGS, and impact prioritization using AHP. A total of 148 impacts were identified and categorized according to the proposed dimensions, resulting in over 1 100 analysed combinations. The results show that the most influential impact is the increased risks generated by the community during the construction phase, while the most persistent and significant effect corresponds to changes in plant diversity during the operational phase. By integrating a multidimensional perspective, the model provides a structured and replicable tool for supporting the design of Environmental Management Plans and public policies. The study also acknowledges current limitations, such as the restricted number of decision-makers considered, and recommends the inclusion of economic criteria and additional stakeholders in future research to improve the model's comprehensiveness and practical utility.

Keywords – Decision making; Environmental Assessment (EA); hydropower projects; impact analysis; Multicriteria Evaluation (MCE); risk management; sustainable development; uncertainty modelling.

Nomenclature	
i	Impact (rows)
j	Impact (columns)
k	Criterion
n	Number of articles reviewed
m	Number of impacts
l	Number of criteria
D	Matrix of Influences Between Impacts
C	Normalized D Matrix
T	Total Influence Matrix
I	Identity Matrix

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s	Sum of all d_{ij} values from matrix D
r_i	Sum of all row i values from matrix T
c_j	Sum of all column j values from matrix T
Z_{ik}	Value of impact i with respect to criterion k
$C_{\mathrm{AHP}(i)}$	AHP valuation of impact i

1. INTRODUCTION

In a context marked by population growth, urbanization in developing nations, and other economic development challenges, investment in infrastructure projects emerges as a fundamental resource to address these essential needs and improve the standard of living [1].

As proposed by Millard [2] and Mofokeng *et al.* [1], projects – particularly infrastructure projects – play a crucial role in the pursuit of a sustainable future by contributing to the improvement of people's quality of life through the importance of social investment [3], fostering economic growth [4] and, in an ethical manner, ensuring the availability of resources for future generations while preserving the environment [5].

Infrastructure projects can be broadly classified according to their structural and spatial characteristics, distinguishing between linear and concentrated developments. Linear projects extend across large distances with the main objective of conveying, transmitting, distributing, connecting, or transporting resources, people, or services through various regions and ecosystems. In contrast, concentrated projects – such as reservoir-based hydroelectric plants – are localized but exert intense and multidimensional pressure on their surrounding environment. These projects typically alter large, well-defined geographic areas and become central nodes of environmental transformation. Their scale and permanence can lead to profound disruptions in local ecosystems, displace communities, and reshape traditional cultural and social dynamics. Given their significant and far-reaching impacts, hydroelectric projects represent a critical case for developing and applying advanced environmental impact assessment models [6].

Accordingly, hydroelectric projects, given their significant impact on surrounding areas, must conduct an impact assessment driven by the pressing need to ensure that all human activities are carried out in harmony with the environment's capacity [7]. The impact assessment must be supported by measurement indicators that facilitate the evaluation of the magnitude of environmental impacts. Additionally, this process faces certain limitations due to the scarcity of information in some projects and the inherent uncertainty associated with them [8]. In this context, it is essential to promote a more comprehensive approach that considers various characteristics that evolve differently over time and space, impacting the involved stakeholders in distinct ways. These characteristics are linked to the project's construction, the nature of the industry in question, and the presence of communities in the region [8]. It is important to highlight that reservoir-based hydroelectric projects are subject to considerable complexity, as they can generate various impacts throughout their life cycle [9], [10]. These impacts range from environmental repercussions that may drive the transition toward alternative hydroelectric approaches [11], [12] to large-scale socio-environmental conflicts linked to the construction of dams in areas of high symbolic value [13].

Consequently, more specifically, the Environmental Impact Assessment (EIA) is crucial for supporting the future planning of projects, considering economic aspects such as costs, benefits, and financing in decision-making [14]. This involves identifying social and environmental costs, in addition to the financial cost associated with the EIA, which can serve as a foundation for future policies in this field [15]. However, the lack of a clear relationship between impacts and the absence of standardization under consistent evaluation criteria in the methods used often allow for the application of arbitrary parameters in temporal, geographical, and administrative terms, based on cost-benefit considerations that favour the evaluator – in other words, the project itself [14]. In many cases, the risks and benefits affecting communities in the areas of influence are not adequately considered [16]. In this context, recent approaches demonstrate how economic criteria can be integrated into multicriteria analyses for energy systems, allowing for more balanced evaluations that incorporate financial, environmental, and social dimensions [17].

That said, and according to a literature review conducted by the authors, evidence of existing gaps has been identified, which justifies the present research.

Table 1 summarizes critical gaps identified in the literature regarding current environmental impact assessment practices, particularly in the context of hydroelectric and similar infrastructure projects. These references highlight the lack of multidimensional analysis, weak causal linkage assessments, and the need for intermediate analytical steps between impact identification and evaluation – issues that the proposed model aims to address.

TABLE 1. SUMMARY OF THE CONTEXT FOUND IN THE LITERATURE

Context	**Author**
Some methodologies evaluate one or two dimensions, usually geographical and temporal, but do not integrate more than two dimensions.	[18]
Social, economic, and environmental issues have been identified, stemming from deficiencies in environmental management plans, particularly due to the lack of analysis of causal relationships between impacts.	[10], [16]
The construction of infrastructure projects generates economic, social, and environmental impacts, which can lead to conflicts in the region.	[6], [18], [19]
Projects can be understood as a complex system of interrelations between the project itself, the community, and even the environment.	[14]
There are methodologies that identify and evaluate the impacts generated by projects, but it is unclear whether methodologies exist that allow for the analysis of impacts as an intermediate step between identification and evaluation.	[2]

In this same line, a generic process has been identified (Fig. 1) regarding the EIA carried out for infrastructure projects, including hydroelectric plants. Currently, the process begins with impact identification, followed by evaluation, and then proceeds to the development of Environmental Management Plans (EMP) [20]. However, certain shortcomings have been identified in this process, as these plans often remain incomplete or fail to fully account for all possible project outcomes [16]. Therefore, it is essential to implement an intermediate step between impact identification and evaluation, allowing for a comprehensive analysis of all connections, influences, and interdependencies. This step would support the creation of Environmental Management Plans and provide clear information to facilitate decision-making for all stakeholders involved in the project [14], [21].

In light of the limitations observed in the formulation of EMPs, it becomes essential to reconsider the traditional EIA process in infrastructure projects. This calls for a more holistic approach that integrates a multidimensional perspective. To this end, the present study proposes an analytical model based on four key dimensions: multicriteria, multi-decision-maker, multitemporal, and multi-spatial. This framework allows for a deeper and more structured analysis of impacts by examining their interconnections, influences, and evolution across space, time, and stakeholder groups.

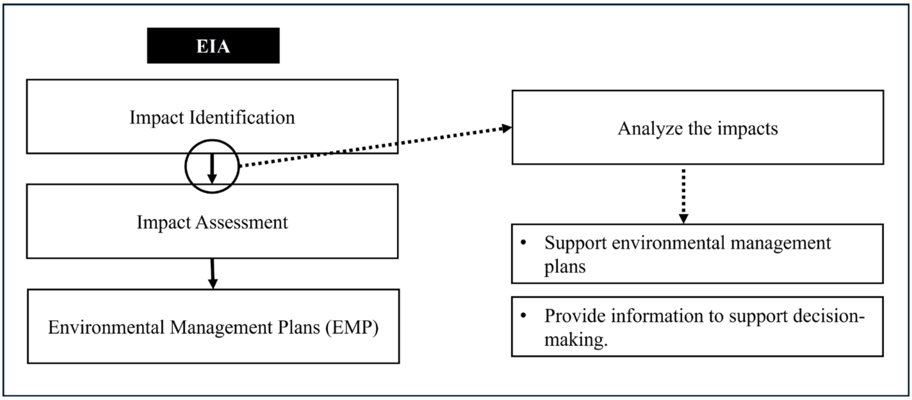

Fig. 1. Summarized EIA Process and Proposal for Process Improvement. Source: Own creation based on [14], [20], [21].

Such an approach aims to strengthen the formulation of EMPs and enhance decision-making with more comprehensive and context-sensitive data. The research is guided by the following question: How can a multidimensional impact analysis model improve the depth and relevance of Environmental Management Plans in reservoir-based hydroelectric projects?

2. METHODOLOGY

The model's methodology is divided into four phases (Fig. 2). In the first phase, the impacts associated with the construction of the reservoir-based hydroelectric project are identified. Secondly, the impacts are categorized within the first three dimensions (multi-spatial, multi-temporal, and multi-decision-maker) based on their internal components, as explained later. Next, the Decision-Making Trial and Evaluation Laboratory (DEMATEL) – Weighted Influence Non-Linear Gauge System (WINGS) methodology [22] is applied to analyse the complex system resulting from the impact categorization. Finally, using the Analytic Hierarchy Process (AHP) methodology, the categorized impacts are evaluated according to the defined criteria for analysis (multi-criteria dimension), ranked, and analysed. One of these key criteria is derived from the DEMATEL-WINGS process.

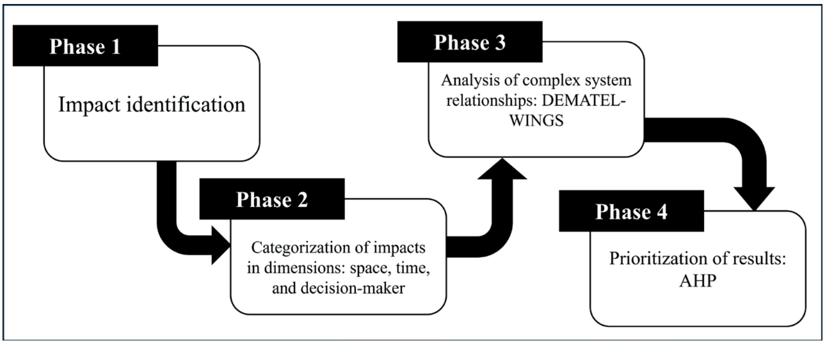

Fig. 2. Phases of the process in four dimensions to analyse the impacts of hydroelectric projects.

Several alternative methodologies, such as MICMAC, ANP, TOPSIS, and PROMETHEE, were analysed during the development of the model. However, each presented limitations that led to their exclusion. For instance, MICMAC is primarily designed for foresight analysis and requires multiple iterations to converge, making it less practical [23]. ANP is less flexible and more complex to apply [24], often lacking the intuitive clarity offered by DEMATEL-WINGS [25]. TOPSIS assumes independence among criteria, which may be unrealistic in complex systems [26]. PROMETHEE, while useful, does not support the hierarchical structuring of criteria, limiting its suitability for multi-level decision problems [27]. These limitations are addressed by the selected combination: AHP allows for hierarchical organization of criteria [27], [28], while DEMATEL-WINGS enables the modelling of interdependencies and bidirectional relationships within complex systems, offering both analytical robustness and practical applicability [24], [25].

To identify the dimensions on which the model is based, a Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) [29], analysis was conducted. The primary databases used were Scopus and SciELO, with the former being one of the largest and highest-quality international meta-search engines [30] and the latter one of the main search platforms in Latin America [31].

The search equation defined for the analysis was:
'(TITLE-ABS-KEY (environmental AND impact AND assessment) AND TITLE-ABS-KEY (hydroelectric)) AND PUBYEAR > 2012 AND PUBYEAR < 2024'.

In Fig. 3 the PRISMA process carried out is illustrated, including its inclusion and exclusion criteria. It is important to note that one of the main inclusion criteria in the PRISMA methodology was the application of impact assessment methods specifically in hydroelectric projects. As a result, the selected articles reflect practical applications of hydroelectric initiatives in diverse regions, including Latin America, Asia, and Africa, allowing for a broader and more representative understanding of the dimensions considered in this study.

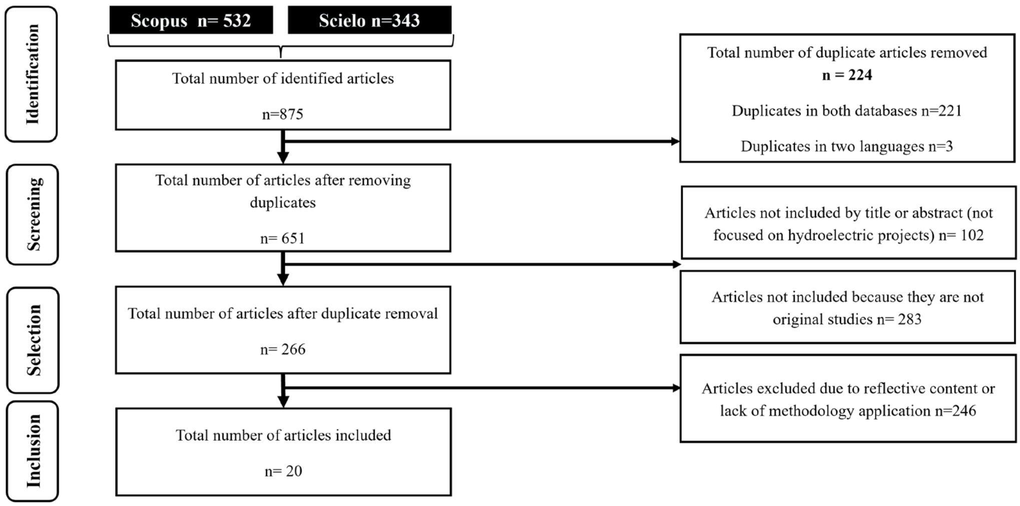

Fig. 3. PRISMA process for literature review.

As a result of the literature review, the ideal dimensions for dividing the model were identified as Multispatial, Multidecisional, Multitemporal, and Multicriteria. These dimensions were defined based on frequency criteria, meaning those that appeared most frequently in the analysed articles concerning the future research factor (Fig. 4).

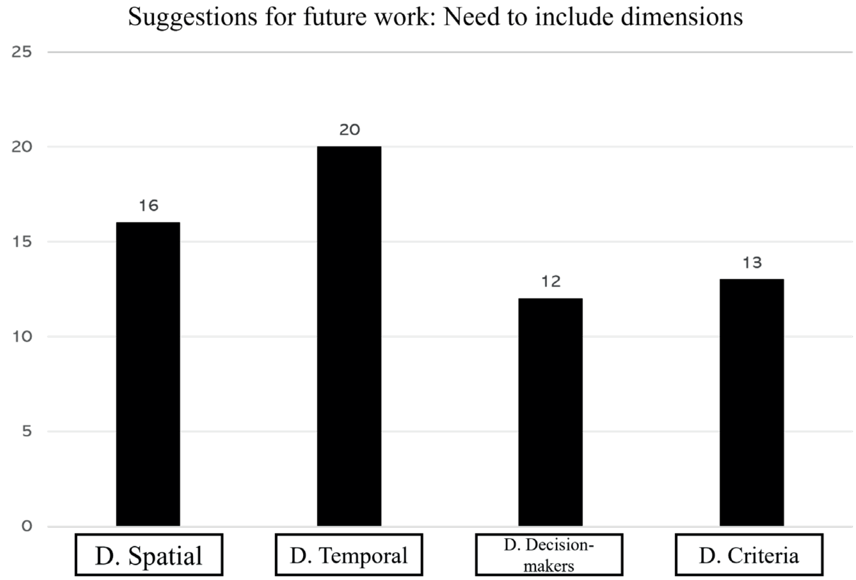

Fig. 4. Number of times the dimension is suggested in the literature review. Source: Own creation based on [32]–[51].

2.1. Impact Identification and Categorization the Impacts in Dimensions

A systematic literature review was conducted using the PRISMA protocol to identify relevant impacts commonly associated with reservoir-based hydroelectric projects. This review served not only to justify the selection of the four analytical dimensions but also to compile a comprehensive list of impacts reported across various studies. The resulting database of impacts forms the foundation for structuring the proposed model, allowing for its adaptation and application to similar real-world scenarios.

In defining the dimensions of analysis, the literature review also guided the criteria used for categorizing impacts. For the multi-decision-maker dimension, the model adopts the approach of Ángel *et al*. [6], identifying two primary stakeholders: the project and the community. These stakeholders are considered across the multi-spatial dimension, which includes three geographical zones typically affected by hydroelectric development: the upstream area, downstream area, and the reservoir itself [16], [34]. For the multi-temporal dimension, the timeline of the project is divided into four stages: planning, construction, operation, and closure [15], [52], [53]. These categorizations serve as the structural basis for organizing and analysing the impacts within the proposed model.

2.2. Analysis of Complex System Relationships Using DEMATEL-WINGS

DEMATEL [25] emerged as a functional tool supporting decision-making, emphasizing its ability to analyse and model interdependent relationships between variables in a complex system, effectively addressing the bidirectional nature and dynamics of possible interactions among system elements. However, WINGS [22] is introduced as an enhancement to the DEMATEL methodology, incorporating two key aspects for analysis. First, it emphasizes the importance of a criterion's relationship with itself. Additionally, it proposes a normalization of criteria to make them dimensionless, allowing for the evaluation of different aspects of relationships within a system. These improvements are not inherently included in the DEMATEL methodology alone [22].

According to Michnik [22], DEMATEL-WINGS is a methodology that can be developed in six steps. First, the matrix **D** of dimensions $m \times m$ is constructed, which can be considered a supermatrix composed of different submatrices. These submatrices represent the actor, temporal, and spatial dimensions in interaction with the other dimensions of the analysis. Matrix **D**, ubicalos m arranges the m categorized impacts along both the horizontal and vertical axes.

For the second step, the influence weight of the categorized impacts within the system must be assigned. This value represents the influence of impact i on impact j in the components d_{ij} of matrix **D**. Regarding the main diagonal, it is defined as the importance of the impact on the entire system. The values are determined according to the scale proposed by the original methodology [22], ranging from 0 to 4: 0 represents 'No influence,' 1 represents 'Low influence,' 2 represents 'Moderate influence,' 3 represents 'High influence,' and 4 represents 'Very high influence.' The same scale is applied to the concept of strength, where 0 indicates 'No strength' and 4 indicates 'Very high strength.'

Fig. 5 presents the structure used to categorize the identified impacts within the analytical dimensions of the model. Unlike Table 3, which lists the general impacts without categorization, Fig. 5 illustrates how each impact is assigned a specific context based on the actor (project or community), spatial location (upstream, downstream, reservoir), and temporal phase (planning, construction, operation, closure), thereby forming the basis for the construction of the D matrix used in the DEMATEL-WINGS analysis.

	Impact 1 - Project – Upstream of the reservoir – Planning	**Impact 2 - Project – Upstream of the reservoir – Planning**	**Impact 3 - Project – Upstream of the reservoir – Planning**	**Impact 4 - Project – Upstream of the reservoir – Planning**	**…**	**Impact m - Community – Downstream of the reservoir – Closure**
Impact 1 - Project – Upstream of the reservoir – Planning					**…**	
Impact 2 - Project – Upstream of the reservoir – Planning					**…**	
Impact 3 - Project – Upstream of the reservoir – Planning					**…**	
Impact 4 - Project – Upstream of the reservoir – Planning					**…**	
…	**…**	**…**	**…**	**…**	**…**	**…**
Impact m - Community – Downstream of the reservoir – Closure					**…**	

Fig. 5. Matrix D of $m \times m$ dimensions that maps the categorized impacts.

In the third step, the values of matrix **D** are normalized, resulting in matrix **C** [22]. This process is carried out using Eq. (1) and Eq. (2).

$$\mathbf{C} = \frac{1}{s}\mathbf{D}, \tag{1}$$

$$s = \sum_{i=1}^{n}\sum_{j=1}^{n} d_{ij}, \tag{2}$$

where **C** is the normalized matrix **D**, and s represents the sum of all d_{ij} values in matrix **D**.

For step 4, the force-influence matrix, referred to as matrix **T**, must be calculated. This matrix accounts for both direct and indirect influences. In this part of the process, Eq. (3) is used to ensure a rapid convergence of results, facilitating matrix operations [22].

$$\mathbf{T} = \mathbf{C} + \mathbf{C}^2 + \mathbf{C}^3 + \ldots = \frac{\mathbf{C}}{\mathbf{I} - \mathbf{C}}, \tag{3}$$

where

T Force-influence matrix. This is the resulting matrix from the process;
C Normalized matrix;
I Identity matrix.

Next, in the following step, the factors r_i Eq. (4) and c_j Eq. (5) are calculated [22].

$$r_i = \sum_{j=1}^{n} t_{ij}, \tag{4}$$

$$c_j = \sum_{i=1}^{n} t_{ij}, \tag{5}$$

where

t_{ij} Value of matrix **t** at position *ij*;
r_i Sum of all *j* values (row *i*) in matrix **t**;
c_j Sum of all *i* values (column *j*) in matrix **t**.

For the final step, corresponding to step 6, the scope factors Eq. (6) and role factors Eq. (7) are calculated for each variable in the system [22].

$$\text{Scope} = r_i + c_j \tag{6}$$

$$\text{Role} = r_i - c_j \tag{7}$$

Scope – this value represents the overall influence of an impact, taking into account both the influence it exerts on others and the influence it receives. In the context of complex networks, this is comparable to the concept of degree of centrality, which reflects the number of connections a node maintains with other nodes [54].

Role – this value reflects the net influence of an impact. A positive value indicates that the impact acts primarily as a cause within the system, influencing other elements. Conversely, a negative value means that the impact is mainly affected by other variables, playing a more passive or dependent role [54].

Both scope and role provide valuable information for decision-making by identifying which variables exert influence or are influenced within the system. This understanding helps determine how changes to specific variables can trigger shifts across the system.

2.3. Prioritization of Results: AHP

The AHP method is a structured tool that facilitates decision-making in complex scenarios involving multiple criteria and options. Its main advantage lies in the hierarchical organization of the problem, allowing decision-makers to systematically analyse each option and compare them with one another. In this approach, criteria serve as evaluation parameters, while options represent the categorized impacts [28]. Additionally, relative weights are assigned to each criterion, aiding in the identification of the most suitable alternative. AHP has become a widely used resource in various scientific and management fields [28], [55].

At this stage, the fourth dimension of the model (Multicriteria) is integrated, defining the criteria under which the AHP analysis is conducted.

As part of the model integration, the first criterion for evaluating the categorized impacts is influence. This criterion emerges from the DEMATEL-WINGS process, where a higher influence suggests that a categorized impact has a more significant effect on the system as a whole [22]. Additionally, magnitude is considered, implying that evaluating it involves assessing the breadth, intensity, and relevance of the generated effects. This provides an understanding of the scale of the resulting alterations or improvements [56]. Finally, understanding the duration of an impact is essential for evaluating temporality, allowing for the anticipation and effective management of both short- and long-term implications [57]. Table 2 presents a summary of the criteria, the weighting scale, and the type of criterion used.

TABLE 2. CRITERIA DEFINED FOR THE MULTICRITERIA DIMENSION

	Definition	**Weighting Scale**	**Type**
Scope	Refers to the combination of direct relationship and control relationship among the considered alternatives. The direct relationship assesses the intensity of the impact of one alternative on another, while the control relationship measures the degree of dependency between them.	The higher ($r + c$), the greater the influence within the system according to DEMATEL-WINGS.	Quantitative
Magnitude	Refers to the measure or extent of changes caused by an event generated by the project.	Null = 0 Insignificant = 1 Moderate = 2 Significant = 3 Critical = 4	Qualitative
Duration	Refers to the period during which the effects resulting from a project-generated event manifest and persist.	Does not occur = 0 Occasional = 1 Temporary = 2 Permanent = 3 Where: Occasional: Less than 1 year. Temporary: Between 1 and 3 years. Permanent: More than 10 years.	Qualitative

The AHP process can be summarized in three fundamental steps. First, the payoff matrix must be constructed (Fig. 6), which evaluates the impacts i concerning the defined criteria k.

	Criteria	Z_1	Z_2	Z_3	…	Z_l
Categorized impacts	i_1					
	i_2					
	i_3					
	i_4					
	i_5					
	…					
	i_m					
Max/Min		+/–	+/–	+/–	…	+/–

Fig. 6. AHP payoff matrix. Source: Own creation based on [28].

The matrix is completed with the corresponding values for each categorized impact and the weights for the matrix. These weights are assigned from the evaluator's perspective, as suggested by the original AHP methodology [28]. Additionally, the direction in which the criterion should be addressed is determined, that is, whether to maximize or minimize the criterion, depending on the case.

As the second step of the AHP process, the normalization Eq. (8) of the categorized criteria values is carried out. This step is necessary because the values are expressed in different units and may have different optimization directions. Normalization ensures that all values are brought to the same (dimensionless) scale [28].

$$Z'_{ik} = \frac{Z_{ik} - Z_k^{\min}}{Z_k^{\max} - Z_k^{\min}}, \tag{8}$$

where

Z'_{ik} represents the evaluation of impact *i* in relation to criterion *k*;

$Z_k^{\min}$ is the minimum identified value for criterion *k*;

$Z_k^{\max}$ is the maximum value obtained for the same criterion.

This process allows for normalizing values within a range between 0 and 1 [28].

Finally, in step 3, the final rating Eq. (9) of each categorized impact is determined by summing the normalized payoffs weighted by the criteria weights. Subsequently, the categorized impacts are consolidated and ranked according to the highest obtained score [28], establishing the order of importance in which projects should be prioritized to begin structuring the EMP.

$$C_{\text{AHP}}(i) = \sum_{k=1}^{1} w_k Z'_{ik} \tag{9}$$

where

$C_{\text{AHP}}(i)$ represents the final score of impact *i*;

W_k is the weight assigned to criterion *k*;

Z'_{ik} is the normalized value of alternative *i* concerning criterion *k*.

3. RESULTS

Based on the literature review, a total of 148 impacts were identified and classified according to the bioethical division of the Sustainable Development Goals (SDGs) proposed by Bórquez Polloni & Lopicich Catalán [5], grouping them into environmental, economic, and social axes. These impacts serve as the foundation for formulating the model and may be adapted to the specific characteristics of each project. Additionally, the PRISMA methodology enabled the categorization of impacts within the first three analytical dimensions. For the multi-decision-maker dimension, the model adopts the approach of Ángel *et al.* [6], distinguishing between two main stakeholders: the project and the community. These stakeholders are considered across the multi-spatial dimension, which includes three key geographic zones: upstream, downstream, and the reservoir area [16], [34]. Regarding the multi-temporal dimension, impacts are associated with four distinct phases of the project: planning, construction, operation, and closure [15], [52], [53]. Fig. 7 illustrates how these categorizations are applied in a structured and sequential manner.

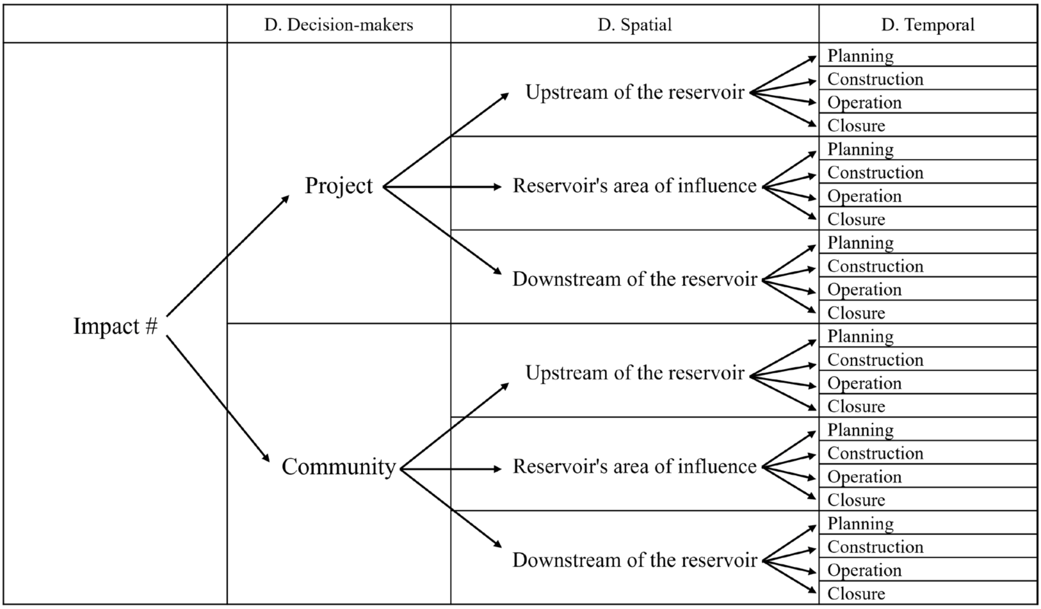

Fig. 7. Classification of impacts in the dimensions.

For example, the structure in which each impact should be categorized should be: 'Impact # – Project – Upstream of the reservoir – Planning', meaning that the impact corresponds to the one generated by the project in the upstream area of the reservoir during the planning phase of the project.

Below are the results in the sequence established by the proposed model, ensuring a consistent structure in the analysis. First, the identification of project impacts is presented. Then, the impacts are categorized according to specific criteria that simplify their understanding and prioritization. Third, the DEMATEL-WINGS analysis is conducted, serving as a key tool to represent the connections between the identified impacts. Finally, the AHP process is applied, assigning relative weights to decision criteria and prioritizing impacts, guiding the selection of the most suitable strategies for their management. This methodology enables a comprehensive and systematic approach to assessing the project's effects.

As previously mentioned, a total of 148 impacts were identified, classified within the three thematic axes of the bioethical approach to the SDGs. Table 3 provides a reference by showcasing some of the identified impacts.

After identification, the impacts were categorized according to each of the dimensions, as stipulated in Fig. 7. This process resulted in a total of 1104 combinations, following the established structure. It is important to clarify that the size is due to the super matrix previously explained in the methodology, which integrates multiple matrices from the different dimensions proposed by the model.

TABLE 3. REFERENCE LIST OF IDENTIFIED IMPACTS FOR THE MODEL BASED ON TABLE A1 IN ANNEX

N°	Impact	Type
1	Modification in hydraulic dynamics, affecting water circulation and movement.	Environmental
2	Changes in the microbiological characteristics of water, impacting the composition and activity of microorganisms.	Environmental
3	Variations in the chemical characteristics of water, such as the concentration of specific substances.	Environmental
…	…	…
79	Population relocation.	Social
80	Change in population dynamics.	Social
81	Change in migration patterns (emigration and immigration).	Social
…	…	…
94	Changes in the economic orientation of the area.	Economic
95	Modification of local economic activities.	Economic
96	Alteration in the use and exploitation of natural resources.	Economic
…	…	…
148	Institutional expectations generation.	Social

Note: This reference list is derived from the literature review.

Table 4 provides an example of how this combination is carried out. This procedure facilitates the comprehensive consolidation of the various characteristics of the detected impacts, offering a thorough and integrated perspective on their nature and interconnection within the analysis model.

TABLE 4. CONCATENATED COMBINATIONS OF CATEGORIZED IMPACTS FOR EACH DIMENSION

Alternatives
Project – Upstream of the reservoir – Planning – 80. Change in population dynamics
Project – Upstream of the reservoir – Planning – 81. Change in migration phenomena (emigration and immigration)
Community – Reservoir – Planning – 92. Increased risks (fires, discharge of toxic substances, inadequate response to flood alerts, among others)
Community – Reservoir – Planning – 93. Segregation of local residents
Project – Downstream basin of the reservoir – Construction – 143. Public concern about the project's effect
Community – Downstream basin of the reservoir – Construction – 80. Change in population dynamics
…

This analysis highlights a categorization that incorporates dimensions often overlooked by some methodologies in their assessments. Specifically, it considers the dimensions of time, space, and multiple stakeholders – elements that enhance the understanding of impacts and provide a comprehensive analysis. These dimensions offer a more detailed and integrated perspective, enriching the Environmental Impact Assessment (EIA) process in reservoir-based hydroelectric projects. The inclusion of temporal dimensions facilitates capturing variability over time, emphasizing how effects can evolve and manifest at different stages of the project's life cycle. The study of spatial dimensions provides valuable insights by distinguishing between effects occurring in different geographical areas, such as upstream, downstream, and within the reservoir. This broader perspective deepens the understanding of impacts and promotes a more holistic analysis. Incorporating temporal and spatial components enhances the ability to identify patterns, trends, and critical areas, thereby optimizing decision-making within environmental, economic, and social contexts. The multiple-stakeholder dimension goes beyond evaluating costs and benefits solely from the project owner's perspective. Instead, it includes the effects on the local community, which primarily bears the negative consequences.

Following this methodology and considering that it operates with a square matrix **D** of size $m \times m$, in this study, based on the classification of impacts, it corresponds to a super matrix of dimensions 1104×1104. It is important to note that some impacts are initially assigned a value of 0, as certain causal relationships are inherently improbable – for instance, the future can hardly influence the past.

Fig. 8 illustrates how the influence and strength values were distributed among the categorized impacts across different dimensions. These values were assigned based on the sources used in the methodology. The study highlights the relationships of influence and strength among the classified impacts. The strength values are positioned along the central diagonal of the matrix.

On the other hand, influence is analysed by examining how the categorized impact in a row directly or indirectly affects the impact classified in a column. To illustrate this, consider the impact '80. Change in population dynamics', caused by the reservoir project upstream during the planning phase, which exhibits a medium strength (equivalent to a value of 2), as shown in position d_{11}.

Looking at position d_{21} we observe that the impact '81. Change in migration phenomena (emigration and immigration)', also caused by the reservoir project upstream during the planning phase, is classified as significant (equivalent to a value of 3) when compared to '80. Change in population dynamics within the same location and stage.

This process was repeated for each of the categorized impacts in matrix **D**, conducting an analysis from left to right and top to bottom.

	Project - Upstream of the reservoir - Planning - 80. Change in population dynamics	**Project - Upstream of the reservoir - Planning - 81. Change in migration phenomena (emigration and immigration)**	**Project - Upstream of the reservoir - Planning - 84. Alteration in the spatial distribution of the population**	**Project - Upstream of the reservoir - Planning - 88. Modification in access to natural resources**	**Project - Upstream of the reservoir - Planning - 90. Generation of expectations in the population**	**…**
Project - Upstream of the reservoir - Planning - 80. Change in population dynamics	2	0	0	3	1	…
Project - Upstream of the reservoir - Planning - 81. Change in migration phenomena (emigration and immigration)	3	2	0	0	0	…
Project - Upstream of the reservoir - Planning - 84. Alteration in the spatial distribution of the population	3	1	2	0	1	…
Project - Upstream of the reservoir - Planning - 88. Modification in access to natural resources	1	4	2	3	0	…
Project - Upstream of the reservoir - Planning - 90. Generation of expectations in the population	3	3	3	3	1	…
…	…	…	…	…	…	…

Fig. 8. Matrix **D**: Assignment of influence weights and strength among categorized impacts.

Within the framework of this specific analysis, Table 5 presents a summary of the 20 most far-reaching categorized impacts. These effects, by exerting a greater direct or indirect influence across the entire system, play a fundamental role in the model. Additionally, data is provided regarding the role each categorized impact plays in the analysis, thereby facilitating a more comprehensive understanding of its significance within the context of the reservoir hydroelectric project.

TABLE 5. ANALYSIS OF SCOPE AND ROLE OF CATEGORIZED IMPACTS

Categorized impacts	**Ranking**	**Type**
Community – Reservoir – Construction – 92. Increased risks (fires, discharge of toxic substances, inadequate response to flood alerts, among others)	1	Cause
Project – Upstream of the reservoir – Operation – 44. Modification of erosion processes	2	Affected
Project – Upstream of the reservoir – Construction – 54. Reduction of areas dedicated to agricultural production	3	Cause
Project – Reservoir – Operation – 75. Change in flora diversity, either increase or decrease	4	Cause
Project – Reservoir – Operation – 24. Emission of Greenhouse Gases (GHG)	5	Cause
Project – Upstream of the reservoir – Construction – 96. Alteration in the use and exploitation of natural resources	6	Cause
Community – Reservoir – Operation – 126. Modification in the pattern of resource use	7	Affected
Project – Reservoir – Construction – 44. Modification of erosion processes	8	Cause
Community – Downstream basin of the reservoir – Operation – 95. Modification in local economic activities	9	Cause
Project – Downstream basin of the reservoir – Operation – 100. Modification in the coverage, quality, and/or availability of community infrastructure and equipment	10	Affected
Project – Reservoir – Operation – 97. Reduction in vehicular mobility	11	Cause
Community – Downstream basin of the reservoir – Operation – 144. Changes in the social and organizational structure of the community	12	Cause
Community – Downstream basin of the reservoir – Construction – 84. Alteration in the spatial distribution of the population	13	Cause
Community – Downstream basin of the reservoir – Operation – 138. Increase in pre–existing conflicts	14	Cause
Project – Upstream of the reservoir – Operation – 80. Change in population dynamics	15	Cause
Project – Reservoir – Operation – 59. Alteration in the habitat of fauna species	16	Cause
Project – Reservoir – Construction – 12. Changes in the sedimentological and hydro geomorphological dynamics of the fluvial system	17	Cause
Community – Reservoir – Construction – 103. Alteration in the coverage, quality, and/or availability of energy and telecommunications services	18	Cause
Project – Reservoir – Operation – 96. Alteration in the use and exploitation of natural resources	19	Affected
Project – Upstream of the reservoir – Construction – 69. Change in the number of species	20	Cause

According to the study, the impact with the greatest overall influence on the system is '92. Increased risks (fires, discharge of toxic substances, inadequate response to flood alerts, among others)' during the construction phase in the reservoir area, caused by the community and playing a causal role. This finding provides a crucial perspective for the development of environmental management plans, considering that the risks associated with potential community actions within the impact area of a hydroelectric reservoir during the operational phase could be linked to incidents such as fires, the release of toxic substances into the dam, or improper responses to flood warnings, among other factors [58].

The second most influential impact identified in the system is '44. Modification of erosive processes' upstream of the reservoir during the operational phase. Given its role as an affected factor, it could have a significant impact on the project. This effect is critical for project management, as its occurrence could lead to increased sedimentation in the reservoir, resulting in equipment deterioration and a reduction in the project's energy efficiency. Consequently, this would lead to higher maintenance costs for the equipment [59], [60].

However, these results are partial since the model's methodology is not yet fully complete. At this stage, the quantitative assessment of the influence criterion has been obtained, which will be carried forward to the next step along with the other two criteria (magnitude and duration) in the AHP process.

The weights assigned to the criteria have been determined and are detailed in Table 6. This table provides an accurate visualization of the normalized weight allocation for each criterion, offering a clear understanding of their relative importance within the framework of the present analysis.

TABLE 6. ASSIGNMENT OF CRITERIA RATING

	Influence	**Magnitude**	**Duration**	**Weight**
Influence	0.24	0.45	0.22	0.30
Magnitude	0.05	0.09	0.13	0.09
Duration	0.71	0.45	0.65	0.61

For the construction of the payoff matrix (Table 7), the values obtained from the literature review and the influence derived from the DEMATEL-WINGS process were used. This matrix, presented in a summarized form for reference, serves as the initial matrix in the AHP process to identify the highest-ranking categorized impacts in descending order. It is important to clarify that, as established in the methodology, the magnitude and duration criteria were assigned numerical values based on their qualitative measurement scale. Additionally, it should be noted that the impacts are arranged in descending order, from highest to lowest influence, as determined by the DEMATEL-WINGS results.

TABLE 7. PAYOFF MATRIX OF THE AHP PROCESS FOR THE ANALYSIS OF CATEGORIZED IMPACTS IN HYDROELECTRIC PROJECTS

Alternative	**Influence**	**Magnitude**	**Duration**
Community – Reservoir – Construction – 92. Increase in human-generated risks (fires, toxic spills, inadequate response to flood alerts, among others)	2.113335	1	1
Project – Upstream of the reservoir – Operation – 44. Modification of erosion processes	2.102082	1	2
Project – Upstream of the reservoir – Construction – 54. Reduction of areas dedicated to agricultural production	2.100969	3	2

Project – Reservoir – Operation – 75. Change in flora diversity, either increase or decrease	2.099857	4	3
Project – Reservoir – Operation – 24. Emission of Greenhouse Gases (GHG)	2.095932	3	3
Project – Upstream of the Reservoir – Construction – 96. Alteration in the use and exploitation of natural resources	2.095364	1	2
Community – Reservoir – Operation – 126. Modification in the pattern of resource use	2.093115	4	3
Project – Reservoir – Construction – 44. Modification of erosive processes	2.086962	3	2
…	…	…	…

Note: The values corresponding to the influence criterion are multiplied by 1000 for better visualization of the information.

Continuing with the process, after assigning values to the payoff matrix, the next step involves normalization, where the total sum of all values for each criterion is adjusted to 1. To achieve this, the sum of each set of values obtained in the previous step is calculated, and then each value is divided by the total sum of that set. This results in the normalized payoff matrix, characterized by the fact that the sum of each column equals 1. Finally, weighting is applied to the criteria to obtain the final result and establish a ranking of the categorized impacts. Table 8 provides a summarized overview of the resulting information.

TABLE 8. RANKING OF CATEGORIZED IMPACTS AS A RESULT OF THE AHP PROCESS

Categorized impact	**Decision**	**Ranking**
Community – Reservoir – Construction – 92. Increase in human–generated risks (fires, toxic spills, inadequate response to flood alerts, among others)	0.0472	5
Project – Upstream of the reservoir – Operation – 44. Modification of erosion processes	0.0459	6
Project – Upstream of the reservoir – Construction – 54. Reduction of areas dedicated to agricultural production	0.0474	4
Project – Reservoir – Operation – 75. Change in flora diversity, either increase or decrease	0.0569	1
Project – Reservoir – Operation – 24. Emission of Greenhouse Gases (GHG)	0.0519	2
Project – Upstream of the Reservoir – Construction – 96. Alteration in the use and exploitation of natural resources	0.0396	8
Community – Reservoir – Operation – 126. Modification in the pattern of resource use	0.0506	3
…	…	…

As observed in Table 8, and in comparison, with Table 7, the impact 'Community – Reservoir – Construction – 92'. Increase in human-generated risks (fires, toxic spills, inadequate response to flood alerts, among others)' ranks fifth in the AHP process. However, in the DEMATEL-WINGS process, it was the highest-ranked impact, occupying the first position. This highlights the importance of expanding the analysis through a multicriteria approach, as it allows for a more comprehensive understanding of the overall effect of an impact by assessing its influence on others, its duration, and its magnitude. An impact with strong influence over others may be less significant if it occurs within a limited space and time, compared to one with lower influence but a prolonged and widespread presence across the analysed territory.

On the other hand, the categorized impact 'Project – Reservoir – Operation – 75. Change in flora diversity, either increase or decrease', which ranked fourth in influence according to the DEMATEL-WINGS process, moves to the first position in the multicriteria analysis when magnitude and duration are considered as additional criteria. This impact is classified as causal. The result indicates that the project has a significant effect on flora diversity within the reservoir area during its operational phase. Its influence is of great magnitude and persists continuously for more than a decade.

In this regard, a noteworthy impact classified as 'Affected' within the top five highest-scoring impacts is 'Community – Reservoir – Operation – 126. Modification in the pattern of resource use.' These finding highlights that the community experiences a direct impact due to the project, particularly in relation to resource use in the reservoir area during its operational phase.

It is essential to highlight that, as a dammed body of water, the reservoir generates significant changes in local water resources, affecting both their availability and quality [61]. Likewise, its formation disrupts the ecosystem's balance, impacting biodiversity and aquatic systems. The alteration of the landscape also influences agricultural activities and the availability of land for use [48]. Consequently, this analysis reflects the substantial impact of the project on the community's living conditions.

According to the logic defined in this model, this study not only enriches and complements the EIA process outlined in Fig. 1, but also serves as a strategic tool for developing long-term prevention and mitigation measures. These measures are not limited solely to the project but require active community involvement and government support. From a holistic perspective, this approach aims to address long-term adverse effects while simultaneously promoting public policies that ensure the continuity of the affected communities' way of life.

It is important to emphasize that these prevention and mitigation strategies go beyond the scope of the project, involving a shared responsibility between communities and governmental entities. In this regard, the implementation of effective public policies is crucial to ensuring that development is not limited solely to the construction of the hydroelectric project but rather contributes to the sustainable progress of all stakeholders involved.

These policies could focus on the preservation of natural resources, the expansion of economic opportunities for the local community, the availability of education and training, and fostering community involvement in decision-making related to the project. Additionally, it would be beneficial to explore the implementation of local economic development programs and the allocation of resources to mitigate long-term social impacts.

Finally, integrating this type of analysis into the planning and execution of hydroelectric projects presents an opportunity to adopt a more equitable and sustainable approach. In this way, development would not only enhance the project's operational efficiency but also contribute to the well-being and stability of local communities.

4. Conclusion

The proposal of a four-dimensional model emerges as a more robust response to address certain limitations, such as the unidimensional analysis of economic or environmental aspects, the lack of integration of multiple dimensions that provide a holistic perspective on impact assessment, the weak participation of multiple stakeholders in decision-making, challenges in environmental management and Environmental Management Plans, as well as impact assessments that are limited in time and space. This approach enables a more thorough and comprehensive study of the effects. Understanding the importance of adapting standard methods to regional circumstances is essential to obtaining more context-specific results. Moreover, the model strengthens the EIA process by offering analytical inputs that support the design of inclusive policies and long-term strategies, contributing to more sustainable and equitable project planning.

The classification of impacts across multi-temporal, multi-spatial, and multi-decision-maker dimensions is a key step for capturing the complexity inherent in hydroelectric projects. This process not only reveals the diversity and extent of potential effects but also provides a practical structure for organizing information in a way that reflects real-world dynamics. For researchers, this approach offers a replicable framework for conducting multidimensional impact analyses in similar contexts. For practitioners, it serves as a decision-support tool that facilitates the identification of critical impacts across different phases and locations, improving the design of targeted Environmental Management Plans and strengthening stakeholder engagement strategies.

The proposal of a four-dimensional analysis model, supported by the DEMATEL-WINGS and AHP methodologies, represents significant progress in understanding the effects of hydroelectric projects. This model not only provides a detailed understanding of causal directions but also accurately identifies those affected and the types of impact. Unlike traditional approaches that analyse dimensions independently, this model is designed to assess impacts at the intersection of spatial, temporal, and stakeholder dimensions, enabling a more holistic interpretation of results and reflecting the complexity of real-world environmental and social interactions. Such precision in classification facilitates effective impact management for the project, the affected communities, and local or national governments. By highlighting the relationships among the studied variables, this holistic approach not only enhances data-driven decision-making but also lays the foundation for implementing prevention, mitigation, and compensation strategies, thereby fostering a more efficient and equitable management of hydroelectric projects. Additionally, it is important to highlight that the proposed 4D model does not aim to replace traditional Environmental Impact Assessment (EIA) methodologies. Instead, it is conceived as a complementary analytical tool that enhances the EIA process. By incorporating four key dimensions – multi-temporal, multi-spatial, multi-decision-maker, and multi-criteria – the model facilitates a more comprehensive analysis of interrelated impacts. This added layer of analysis supports the design of more effective Environmental Management Plans and improves decision-making by offering a deeper understanding of impact dynamics across time, space, and stakeholder perspectives.

The inclusion of the influence criterion, based on the $r + c$ equation from the DEMATEL-WINGS methodology, represents an advancement over previous approaches proposed in the literature, such as the synergy criterion suggested by Conesa *et al.* [62] in their research. This option enhances the study of effects in hydroelectric projects by highlighting both direct and indirect connections among various options, thus offering a broader and more detailed perspective on impact interrelations. Unlike the synergy method, the influence criterion underscores the ability of impacts to influence one another, facilitating a more nuanced understanding of complex relationships.

For future research, it is recommended to expand the AHP analysis approach by incorporating a broader range of evaluation criteria. Specifically, it is suggested to include economic criteria, as these are often key factors in assessing hydroelectric energy projects. Integrating financial criteria, such as costs and revenues, would enhance the understanding of impacts from a more comprehensive perspective.

Additionally, since only two stakeholders were included, it is advisable to consider a greater number of decision-makers in the analysis, incorporating local governments and other significant participants. The involvement of diverse decision-makers will enrich the evaluation by presenting a variety of viewpoints and considerations. For instance, the participation of local governments could offer an alternative perspective on community-scale effects and facilitate the implementation of public policies aligned with local needs.

REFERENCES

[1] Mofokeng M., Alhassan A. L., Zeka B. Public–private partnerships and economic growth: a sectoral analysis from developing countries. *International Journal of Construction Management* 2024:24(10):1029–1037. https://doi.org/10.1080/15623599.2023.2217374

[2] Millard S. Macroeconomics and Climate Change. *National Institute and Economic Review.* 2023:264:1–7. https://doi.org/10.1017/nie.2023.18

[3] Yu A. Social Investment National Evaluation (SINE). A multi-phase study to explore Social Investment within Aotearoa – New Zealand. The University of Auckland, 2023 [Online]. [Accessed 23.09.2023]. Available: https://researchspace.auckland.ac.nz/items/cd4ac59f-3fb3-4c98-85bd-487925465f37

[4] CEPAL. Inversión pública. Observatorio Regional de Planificación para el Desarrollo de América Latina y el Caribe (Public investment. Regional Planning Observatory for the Development of Latin America and the Caribbean). [Online]. [Accessed 23.09.2023]. Available: https://observatorioplanificacion.cepal.org/es/inversion-publica (In Spanish).

[5] Bórquez Polloni B., Lopicich Catalán B. The bioethical dimension of the Sustainable Development Goals (SDGs). *Revista de Bioetica y Derecho*. 2017:41:121-139 [Online]. [Accessed 23.09.2023]. Available: www.bioeticayderecho.ub.edu

[6] Ángel E., Carmona S. I., Villegas L. C. Gestion Ambiental En Proyctos De Desarrollo (Environmental Management in Development Projects), 2010. [Online]. [Accessed: 30.09.2023]. Available: https://minas.medellin.unal.edu.co/images/Centro-Editorial/Gestion_ambiental_en_proyectos.pdf (In Spanish).

[7] Weidner T., Tulus V., Guillén-Gosálbez G. Environmental sustainability assessment of large-scale hydrogen production using prospective life cycle analysis. *International Journal of Hydrogen Energy* 2023:48(22):8310–8327. https://doi.org/10.1016/j.ijhydene.2022.11.044

[8] Saxe S., Guven G., Pereira L., Arrigoni A., Opher T., Roy A., Arceo A., Raesfeld S. S. V., Duhamel M., McCabe B., Panesar D. K., MacLean H. L., Posen I. D. Taxonomy of uncertainty in environmental life cycle assessment of infrastructure projects. *Environmental Research Letters* 2020:15(8):083003. https://doi.org/10.1088/1748-9326/ab85f8

[9] Hatamkhani A., Moridi A., Randhir T. O. Sustainable planning of multipurpose hydropower reservoirs with environmental impacts in a simulation–optimization framework. *Hydrology Research* 2023:54(1):31–48. https://doi.org/10.2166/nh.2022.084

[10] Savio A., Marchi B., Roletto A., Milano G., Zanoni S. Sustainable Operating Rooms: A Comprehensive Framework for Environmental Impact Analysis. *Environmental and Climate Technologies* 2024:28(1):842–854. https://doi.org/10.2478/rtuect-2024-0064

[11] Lau H. C. Decarbonization of ASEAN's power sector: A holistic approach. *Energy Reports* 2023:9:676–702. https://doi.org/10.1016/j.egyr.2022.11.209

[12] Brence K., Kudurs E., Valters K., Blumberga D. Twinned Renewable Energy Accumulation: Case of Wind and Hydro Energy. *Environmental and Climate Technologies* 2023:27(1):696–710. https://doi.org/10.2478/rtuect-2023-0051

[13] Campos-Medina F., Noguer Aceitón V. Construcción de nuevas territorialidades; el territorio como horizonte para la acción en la reforma energética chilena (Construction of new territorialities: territory as a horizon for action in Chilean energy reform). *Revista de geografía Norte Grande* 2023:85:1–21. https://doi.org/10.4067/S0718-34022023000200101

[14] Asplund T., Hjerpe M. Project coordinators' views on climate adaptation costs and benefits–justice implications. *Local Environment, The International Journal of Justice and Sustainability* 2020:25(2):114-129. https://doi.org/10.1080/13549839.2020.1712340

[15] Altaf M., Alaloul W. S., Musarat M. A., Qureshi A. H. Life cycle cost analysis (LCCA) of construction projects: sustainability perspective. *Environment, Development and Sustainability* 2023:25(11):12071–12118. https://doi.org/10.1007/s10668-022-02579-x

[16] Sengupta U., Sengupta U. SDG-11 and smart cities: Contradictions and overlaps between social and environmental justice research agendas. *Frontiers in Sociology* 2022:7. https://doi.org/10.3389/fsoc.2022.995603

[17] Jumintono J., Salim M. A., Lin M.-H., Alshalal M. H., Ali M. H., Braiber H. T. Multi-Criteria Problems of Energy Consumption in Buildings Considering Technical and Economic Indices. *Environmental and Climate Technologies* 2023:27(1):379–390. https://doi.org/10.2478/rtuect-2023-0028

[18] Fonseca A., Gibson R. B. Testing an ex-ante framework for the evaluation of impact assessment laws: Lessons from Canada and Brazil. *Environmental Impacts Assessment Review* 2020:81:106355. https://doi.org/10.1016/j.eiar.2019.106355

[19] Ruiz Citores A. Análisis del atlas de justicia ambiental EJOLT (Analysis of the EJOLT Environmental Justice Atlas). Álava, 2017 [Online]. [Accessed: 02.05.2023]. Available: https://addi.ehu.es/bitstream/handle/10810/30032/TFG_Ruiz.pdf?sequence=1&isAllowed=y

[20] Laverde-Salazar J. F., Torres M. A., Cardona-Valencia D. Análisis comparativo de la Evaluación de Impacto Ambiental, Evaluación ex ante y ex post (Comparative analysis of Environmental Impact Assessment, ex ante and ex post evaluation). *Revista ION* 2023:36(3):15–32. https://doi.org/10.18273/revion.v36n3-2023002

[21] Caro-Gonzalez A. L., Toro J., Zamorano M. Effectiveness of environmental impact statement methods: A Colombian case study. *Journal of Environmental Management* 2021:300:113659. https://doi.org/10.1016/j.jenvman.2021.113659

[22] Michnik J. Weighted Influence Non-linear Gauge System (WINGS) – An analysis method for the systems of interrelated components. *European Journal of Operational Research* 2013:228(3):536-544. https://doi.org/10.1016/j.ejor.2013.02.007

[23] Iqbal M., Ma J., Ahmad N., Ullah Z., Hassan A. Energy-Efficient supply chains in construction industry: An analysis of critical success factors using ISM-MICMAC approach. *International Journal of Green Energy* 2023:20(3):265–283. https://doi.org/10.1080/15435075.2022.2038609

[24] Shakeri H., Khalilzadeh M. Analysis of factors affecting project communications with a hybrid DEMATEL-ISM approach (A case study in Iran). *Heliyon* 2020:6(8):e04430. https://doi.org/10.1016/j.heliyon.2020.e04430

[25] Teymourifar A., Trindade M. A. M. Using DEMATEL and ISM for Designing Green Public Policies Based on the System of Systems Approach. *Sustainability* 2023:15(14):10765. https://doi.org/10.3390/su151410765

[26] Lourenzutti R., Krohling R. A. A generalized TOPSIS method for group decision making with heterogeneous information in a dynamic environment. *Information Sciences* 2016:330:1–18. https://doi.org/10.1016/j.ins.2015.10.005

[27] Chakraborty S., Raut R. D., Rofin T. M., Chakraborty S. A comprehensive and systematic review of multi-criteria decision-making methods and applications in healthcare. *Healthcare Analytics* 2023:4:100232. https://doi.org/10.1016/j.health.2023.100232

[28] Saaty T. L. Decision making with the analytic hierarchy process. *International Journal of Services Sciences* 2008:1(1):83. https://doi.org/10.1504/IJSSCI.2008.017590

[29] Albhirat M. M., Rashid A., Rasheed R., Rasool S., Zulkiffli S. N. A., Zia-ul-Haq H. M., Mohammad A. M. The PRISMA statement in enviropreneurship study: A systematic literature and a research agenda. *Cleaner Engineering and Technology* 2024:18:100721. https://doi.org/10.1016/j.clet.2024.100721

[30] Pranckutė R. Web of Science (WoS) and Scopus: The Titans of Bibliographic Information in Today's Academic World. *Publications* 2021:9(1):12. https://doi.org/10.3390/publications9010012

[31] Vuotto A., Di Césare V., Pallotta N. Fortalezas y debilidades de las principales bases de datos de información científica desde una perspectiva bibliométrica (Strengths and weaknesses of the main scientific information databases from a bibliometric perspective). *Palabra Clave (La Plata)* 2020:10(1):e101. https://doi.org/10.24215/18539912e101 (In Spanish)

[32] Villegas C., Jesús P. Análisis y Recalificación de Impactos Ambientales generados por el Proyecto Central Hidroeléctrica San Gabán III en Carabaya (Analysis and Reclassification of Environmental Impacts generated by the San Gabán III Hydroelectric Plant Project in Carabaya). Puno, 2015. Universidad Católica de Santa María, 2017. [Online]. [Accessed 22.09.2023]. Available: https://repositorio.ucsm.edu.pe/handle/20.500.12920/5987?show=full

[33] Moscoso L., Montealegre J. Identificación de impactos generados en la flora terrestre por la implementación de pequeñas centrales hidroeléctricas, en los municipios de Alejandría y Sonsón, región oriente del departamento de Antioquia (Identification of impacts on terrestrial flora caused by the implementation of small hydroelectric plants in the municipalities of Alejandría and Sonsón, eastern region of the department of Antioquia). Universidad de Manizalez, 2013.

[34] Asaduzzaman M. Rahman Md. M. Impacts of Tipaimukh Dam on the Down-stream Region in Bangladesh: A Study on Probable EIA. *Journal of Science Foundation* 2016:13(1):3–10. https://doi.org/10.3329/jsf.v13i1.27827

[35] Tedjio R. C., Talla E. T., Nana E. D. Complementarity of two impact assessment tools: the case of a hydroelectric power plant in one of Africa's last hardwood forests in eastern Cameroon. *Impact Assessment and Project Appraisal* 2016:34(3):261–266. https://doi.org/10.1080/14615517.2016.1184503

[36] Loayza F. Strategic Environmental Assessment in the World Bank: Learning from Recent Experience and Challenges. *The World Bank Open Knowledge Repository* 2012. https://doi.org/10.1596/27119

[37] Rowe A. Rapid impact evaluation. *Evaluation* 2019:25(4):496–513. https://doi.org/10.1177/1356389019870213

[38] Becerra Barrantes J. C. Huella hídrica del proceso de harina de pescado y su impacto ambiental de una planta industrial pesquera de Chimbote (Water footprint of the fishmeal process and its environmental impact at a fishing industrial plant in Chimbote). Univ. Nacional del Santa, Perú, 2023 [Online]. [Accessed 23.09.2023]. Available: https://repositorio.uns.edu.pe/bitstream/handle/20.500.14278/4295/52766.pdf?sequence=1&isAllowed=y

[39] Peláez L., Diego J. Evaluación del impacto ambiental de proyectos de Desarrollo (Environmental impact assessment of development projects), 2022. [Online]. [Accessed 23.09.2023]. Available: https://repositorio.unal.edu.co/handle/unal/3257 (In Spanish)

[40] Veronez D. V., Abe K. C., Miraglia S. G. E. K. Health Impact Assessment of the construction of hydroelectric dams in Brazil. *Chronicles of Health Impact Assessment* 2018:3(1):11–36. https://doi.org/10.18060/21777

[41] Zapata L. F. B. Impactos Ecológicos Generados Por La Construcción De Centrales Hidroeléctricas con embalses Sobre La Biota Acuátina (Ecological Impacts Generated by the Construction of Hydroelectric Power Plants with Reservoirs on Aquatic Biota). Universidad de Antioquia, Medellín, 2020 [Online]. [Accessed 07.02.2024]. Available: https://bibliotecadigital.udea.edu.co/bitstream/10495/15102/1/BetancurLuisa_2020_ImpactosEcologicosEmbalses.pdf (In Spanish)

[42] Arteaga G., García J., Tejada J., Rodriguez R. Estrategia alternativa para la priorización de proyectos de infraestructura (Alternative strategy for prioritizing infrastructure projects). *Banco Interamericano de Desarrollo* 2019. https://doi.org/10.18235/0001987

[43] Zhang S., Sun B., Yan L., Wang C. Risk identification on hydropower project using the IAHP and extension of TOPSIS methods under interval-valued fuzzy environment. *Natural Hazards* 2013:65(1):359–373. https://doi.org/10.1007/s11069-012-0367-2

[44] Arboleda J. A. Manual de evaluación de impacto ambiental de proyectos, obras o actividades (Manual for environmental impact assessment of projects, works or activities). Medellín, 2008.

[45] Dimitriou H. T., Ward E. J., Dean M. Presenting the case for the application of multi-criteria analysis to mega transport infrastructure project appraisal. *Research in Transportation Economics* 2016:58:7–20. https://doi.org/10.1016/j.retrec.2016.08.002

[46] Tsamboulas D. A. A tool for prioritizing multinational transport infrastructure investments. *Transport Policy* 2007:14(1):11–26. https://doi.org/10.1016/j.tranpol.2006.06.001

[47] Pillajo R. Opción metodológica para estudios de expansión de capacidad generación (Methodological option for generation capacity expansion studies). *Revista Técnica "Energía"* 2007:3(1). https://doi.org/10.37116/revistaenergia.v3.n1.2007.275 (In Spanish)

[48] Roque N., Nuñez L., Vásquez A. Impactos ambientales significativos generados por la actividad de la empresa Alpes Chiclayo S.A.C. (Significant environmental impacts generated by the activity of the company Alpes Chiclayo S.A.C.) *Agroindustrial Science* 2016:6(1). https://doi.org/10.17268/agroind.science.2016.01.10 (In Spanish)

[49] Torres Sibille A. del C., Cloquell-Ballester V.-A., Cloquell-Ballester V.-A., Darton R. Development and validation of a multicriteria indicator for the assessment of objective aesthetic impact of wind farms. *Renewable and Sustainable Energy Reviews* 2009:13(1):40–66. https://doi.org/10.1016/j.rser.2007.05.002

[50] Zulaica L., Celemín J. P. Análisis territorial de las condiciones de habitabilidad en el periurbano de la ciudad de Mar del Plata (Argentina), a partir de la construcción de un índice y de la aplicación de métodos de asociación especial (Territorial analysis of living conditions in the peri-urban area of the city of Mar del Plata (Argentina), based on the construction of an index and the application of spatial association methods). *Revista de geografía Norte Grande* 2008:41. https://doi.org/10.4067/S0718-34022008000300007 (In Spanish)

[51] Sacchi R., Terlouw T., Siala K., Dirnaichner A., Bauer C., Cox B., Mutel C., Daioglou V., Luderer G. Prospective Environmental Impact assement (premise): A streamlined approach to producing databases for prospective life cycle assessment using integrated assessment models. *Renewable and Sustainable Energy Reviews* 2022:160:112311. https://doi.org/10.1016/j.rser.2022.112311

[52] Wang T., Chen H.-M. Integration of building information modeling and project management in construction project life cycle. *Automation in Construction* 2023:150:104832. https://doi.org/10.1016/j.autcon.2023.104832

[53] Departamento Nacional de Planeación, Manual conceptual de la Metodología General Ajustada (MGA) (National Planning Department, Conceptual Manual of the Adjusted General Methodology (MGA)). Bogotá, 2023. [Online]. [Accessed 10.05.2023]. Available: https://mgaayuda.dnp.gov.co/Recursos/Documento_conceptual_2023.pdf

[54] Ugurlu O. Comparative analysis of centrality measures for identifying critical nodes in complex networks. *Journal of Computational Science* 2022:62:101738. https://doi.org/10.1016/j.jocs.2022.101738

[55] Canco I., Kruja D., Iancu T. AHP, a Reliable Method for Quality Decision Making: A Case Study in Business. *Sustainability* 2021:13(24):13932. https://doi.org/10.3390/su132413932

[56] Castelblanco G., Guevara J., Rojas D., Correa J., Verhoest K. Environmental Impact Assessment Effectiveness in Public–Private Partnerships: Study on the Colombian Toll Road Program. *Journal of Management in Engineering* 2023:39(2). https://doi.org/10.1061/JMENEA.MEENG-5015

[57] Berrío Giraldo L. I. Selección y priorización de impactos ambientales de proyectos de desarrollo lineal para su posterior valoración económica – Líneas de Transmisión (Selection and prioritization of environmental impacts of linear development projects for subsequent economic valuation – Transmission Lines). Universidad Nacional de Colombia, Medellín, 2014. [Online]. [Accessed 19.01.2024]. Available: https://repositorio.unal.edu.co/bitstream/handle/unal/53860/1037604353.2015.pdf?sequence=1&isAllowed=y (In Spanish)

[58] Mayeda A. M., Boyd A. D. Factors influencing public perceptions of hydropower projects: A systematic literature review. *Renewable and Sustainable Energy Reviews* 2020:121:109713. https://doi.org/10.1016/j.rser.2020.109713

[59] Cantelli A., Paola C., Parker G. Experiments on upstream-migrating erosional narrowing and widening of an incisional channel caused by dam removal. *Water Resources Research* 2004:40(3). https://doi.org/10.1029/2003WR002940

[60] Ministry of Environment and Sustainable Development. List of Specific Environmental Impacts 2021. [Online]. Available: https://www.minambiente.gov.co/wp-content/uploads/2022/04/Listado-de-Impactos-Ambientales-Especificos-2021-V.4.pdf

ANNEX

TABLE A1. LIST OF IDENTIFIED IMPACTS FOR HYDROELECTRIC PROJECTS BASED ON [60]

N°	Impact	Type
1	Modification in hydraulic dynamics, affecting water circulation and movement.	Environmental
2	Changes in the microbiological characteristics of water, impacting microorganism composition and activity.	Environmental
3	Variations in the chemical characteristics of water, such as the concentration of specific substances.	Environmental
4	Changes in the dissolved oxygen concentration in water, crucial for aquatic life.	Environmental
5	Variation in the biochemical oxygen demand (BOD) in water.	Environmental
6	Changes in the chemical oxygen demand (COD) during chemical processes in the water.	Environmental
7	Increase or decrease in sedimentation at the bottom of the water body.	Environmental
8	Changes in water temperature, with direct impacts on aquatic flora and fauna.	Environmental
9	Modifications in the turbidity of the water due to suspended particles.	Environmental
10	Variation in aquifer recharge, affecting underground water deposits.	Environmental
11	Alteration in the course of surface water bodies, such as rivers or streams.	Environmental
12	Changes in the sedimentological and hydro geomorphological dynamics of the river system.	Environmental
13	Modifications in the hydrological regime and drainage pattern.	Environmental
14	Interruption of surface water flow continuity.	Environmental
15	Transformation of lotic systems to lentic systems.	Environmental
16	Increase or decrease in water availability for aquatic transportation.	Environmental
17	Variation in water availability for the preservation of aquatic flora and fauna.	Environmental
18	Changes in water availability for fishing and aquaculture.	Environmental
19	Increase or decrease in water availability for navigation.	Environmental
20	Increase or decrease in water availability for livestock use.	Environmental
21	Modification of the volumetric flow of water.	Environmental
22	Variation in ecological and environmental flow.	Environmental
23	Changes in water availability for recreational use.	Environmental
24	Emission of Greenhouse Gases (GHG).	Environmental
25	Increase in the concentration of particulate matter in the air.	Environmental
26	Changes in the local microclimate.	Environmental
27	Modification in the direction of local winds.	Environmental
28	Changes in the spatial distribution of precipitation.	Environmental
29	Increase in evaporation in the area.	Environmental
30	Increase in vegetation evapotranspiration.	Environmental
31	Increase in the frequency of atmospheric electrical discharges.	Environmental
32	Changes in the relative humidity of the air.	Environmental
33	Variation in cloudiness in the region.	Environmental

N°	Impact	Type
34	Increase or decrease in the occurrence of droughts.	Environmental
35	Changes in precipitation patterns in the area.	Environmental
36	Variation in wind speed in the locality.	Environmental
37	Modification in local temperature.	Environmental
38	Increase or decrease in the solar radiation received.	Environmental
39	Variation in environmental noise levels.	Environmental
40	Increase in the perception of offensive odours (in reservoirs without cover removal).	Environmental
41	Modification in soil geochemistry.	Environmental
42	Alteration in the dynamics of geomorphological processes.	Environmental
43	Change in land cover.	Environmental
44	Modification of erosive processes.	Environmental
45	Changes in sedimentary processes.	Environmental
46	Modifications in the stability of the terrain.	Environmental
47	Alteration in morphodynamical processes.	Environmental
48	Changes in the geomechanical characteristics of rock mass stability.	Environmental
49	Changes in the geomechanical characteristics of land stability.	Environmental
50	Destabilization of slopes.	Environmental
51	Change in land use.	Environmental
52	Reduction of areas designated for environmental conservation and protection.	Environmental
53	Reduction of areas designated for cultural heritage conservation and protection.	Environmental
54	Decrease in areas dedicated to agricultural production.	Environmental
55	Increase in areas designated for forest production.	Environmental
56	Reduction of areas designated for recreation.	Environmental
57	Decrease in the population of fish species.	Environmental
58	Displacement or displacement of fauna.	Environmental
59	Alteration in the habitat of species of fauna.	Environmental
60	Change in the dynamics of the food chain.	Environmental
61	Modification in species composition.	Environmental
62	Interruption of ecological connectivity corridors.	Environmental
63	Change in ecological connectivity.	Environmental
64	Habitat fragmentation.	Environmental
65	Modification in the habitat of aquatic species.	Environmental
66	Impact on the health of populations of environmentally important aquatic species.	Environmental
67	Impact on populations of aquatic species.	Environmental
68	Impact on the health of economically important aquatic species.	Environmental
69	Change in the number of species.	Environmental
70	Variation in species abundance.	Environmental
71	Modification in the habitat of plant species.	Environmental
72	Reduction in vegetation cover.	Environmental

N°	Impact	Type
73	Decrease in plant biomass.	Environmental
74	Fragmentation of ecosystems.	Environmental
75	Change in flora diversity, either increase or decrease.	Environmental
76	Variation in populations of species of economic importance.	Environmental
77	Changes in populations of species of ecological importance.	Environmental
78	Changes in populations of species of cultural importance.	Environmental
79	Relocation of populations.	Social
80	Change in population dynamics.	Social
81	Change in migration phenomena (emigration and immigration).	Social
82	Modification in land occupation.	Social
83	Change in demographic structure.	Social
84	Alteration in the spatial distribution of the population.	Social
85	Increase in transient population.	Social
86	Transformation of the urban environment.	Social
87	Change in the aesthetic perception of the landscape.	Social
88	Modification in access to natural resources.	Social
89	Displacement of communities.	Social
90	Generation of expectations in the population.	Social
91	Increase in social vulnerability.	Social
92	Increase in risks.	Social
93	Segregation of local residents.	Social
94	Changes in the economic orientation of the area.	Economic
95	Modification in local economic activities.	Economic
96	Alteration in the use and exploitation of natural resources.	Economic
97	Reduction in vehicular mobility.	Economic
98	Changes in traffic safety.	Economic
99	Variation in travel times and patterns.	Economic
100	Modification in the coverage, quality, and/or availability of community infrastructure and equipment.	Economic
101	Changes in coverage, quality, and/or access to healthcare services.	Economic
102	Changes in coverage, quality, and/or access to educational services.	Economic
103	Alteration in coverage, quality, and/or availability of energy and telecommunications services.	Economic
104	Modification in public services conditions.	Economic
105	Increase or decrease in unplanned settlements.	Economic
106	Impact on natural resources essential for subsistence activities.	Economic
107	Change in primary sector productive activities.	Economic
108	Change in secondary sector productive activities.	Economic
109	Change in the composition of the local labour force.	Economic
110	Modification in employment dynamics.	Economic
111	Change in ownership structure.	Economic

N°	Impact	Type
112	Alteration in short-term employment trends.	Economic
113	Alteration in medium-term employment trends.	Economic
114	Change in traditional economic activities.	Economic
115	Change in productive systems.	Economic
116	Disincentive to traditional productive systems.	Economic
117	Increase or decrease in local inflation.	Economic
118	Changes in the supply of goods and services.	Economic
119	Decrease in agricultural production.	Economic
120	Decrease in fishing production.	Economic
121	Increase in the cost of living.	Economic
122	Increase in land value.	Economic
123	Increase in merchandise value.	Economic
124	Change in productive activities.	Economic
125	Change in housing conditions.	Economic
126	Modification in resource use patterns.	Economic
127	Change in the social environment.	Economic
128	Loss of traditional culture.	Economic
129	Changes in the community organizational structure.	Social
130	Generation of conflicts between different actors, whether public or private.	Social
131	Generation of conflicts related to the distribution of benefits.	Social
132	Generation of conflicts over water use.	Social
133	Generation of conflicts over resource use.	Social
134	Generation of conflicts over land use.	Social
135	Increase in criminal activities.	Social
136	Increase in the presence of illegal armed actors.	Social
137	Increase in civil disturbances.	Social
138	Increase in pre-existing conflicts.	Social
139	Modification of participation instances and mechanisms.	Social
140	Increase in illicit activities.	Social
141	Increase in violence.	Social
142	Increase in domestic violence cases.	Social
143	Concerns in the population about the effects of the project.	Social
144	Changes in the social and organizational structure of the community.	Social
145	Change in the community management capacity.	Social
146	Presence of new actors in the local and regional scene.	Social
147	Increase in the interaction of traditional communities with outsiders.	Social
148	Generation of institutional expectations.	Social