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Hierarchy of environmental impacts in hydroelectric projects established in mountain ecosystems

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Abstract: In Bolivia, hydroelectric projects are gaining relevance as a source of renewable energy, which is why there is little record of specific experiences on the implementation of hydroelectric projects in mountain areas that include an analysis of the environment within the framework of sustainability energetic. The present study takes a hydroelectric reservoir project established in a mountain ecosystem as a unit of analysis to demonstrate that a hierarchy of environmental impacts responds more precisely to the environmental dimension, according to its technical and ecosystem characteristics. The development of the work starts with the analysis of the information recorded in the Environmental Impact Assessment Study - EEIA and based on this information, a procedure is carried out to rank the environmental impacts with the use of matrix, qualitative and quantitative methods, in addition to the use of specialized software. Finally, it is concluded that there are no standard evaluations, and it is affirmed that the EIA of any hydro-energy project, whether established or not, in a mountain ecosystem, is a complex and unique problem. Therefore, a hierarchical ranking of environmental impacts in an initial and particular way to the project site area contributes in a real and effective way to an environmental sustainability of the intervened ecosystem, within the framework of Sustainable Energy Development.

Key words: reservoir hydroelectric projects; mountain ecosystems; energy sustainability; environmental impact assessment; hierarchy of environmental impacts

1 Introduction

The Environmental Impact Assessment - EIA is an environmental policy instrument currently adopted in many jurisdictions (countries, regions or local governments, as well as international organizations such as development banks and private entities). It is recognized in international treaties as a potentially very effective mechanism for preventing environmental damage and promoting sustainable development. Although the EIA does not achieve sustainable development "itself", it can help guide decision-makers towards this direction in the early stages, which is why the development of research work reveals creative and efficient alternatives, and makes actions compatible with the requirements and demands of the environmental regulations in force in the Plurinational State of Bolivia.

Likewise, the *Political Constitution of the Plurinational State of Bolivia* establishes that it is the duty of the State and the population to conserve, protect and make sustainable use of natural resources and biodiversity, as well as to maintain the balance of the environment. It also establishes that those who carry out activities that have an impact on the environment must, at all stages of their activity, avoid, minimize, mitigate, remedy, repair and compensate for damage to the environment and people's health. Likewise, Law 1333, - *Environmental Law*, establishes the obligation to apply the EIA to all activities, works or projects and to ensure the environmental compatibility of other laws, such as the *Framework Law of Mother Earth and Integral Development for Living Well* - Law No. 300, in which the Plurinational State of Bolivia establishes as part of environmental management, the precautionary principle and the priority of prevention, enshrining avoidance as a general rule.

Due to the diversity of the topographic conditions of the Bolivian territory, the hydroelectric projects established in mountain ecosystems present a series of particularities that define their multipurpose character in terms of water supply, either for consumption or for the development of agricultural practices, within the framework of food security, an aspect that limits the condition for the case study of hydroelectric project. However, it is conceived as a project that will meet the electricity demand needs of the surrounding populations, through the transmission line foreseen for the execution of the project, for connection to the National Interconnected System - NIS. Therefore, it is considered a project that "guarantees access to affordable, safe, sustainable and modern energy for all".

In this context, the study questions the following:

Does the prioritization of the environmental impacts of the hydroelectric project under study, which is located in a mountainous area, contribute to the environmental sustainability of the intervened ecosystem, within the framework of a sustainable energy development?

2 Method

The research had a qualitative and quantitative approach because it worked with data from the diagnosis and prediction stage obtained from the EEIA.

The type of research is correlational - explanatory, because it is based on an existing study, which is complemented and differences are defined, and it seeks to provide a solution to certain problems.

Data was collected from the existing study and from secondary information sources such as publications, books and digital platforms based on GIS.

The methodological framework is developed according to the following structure:

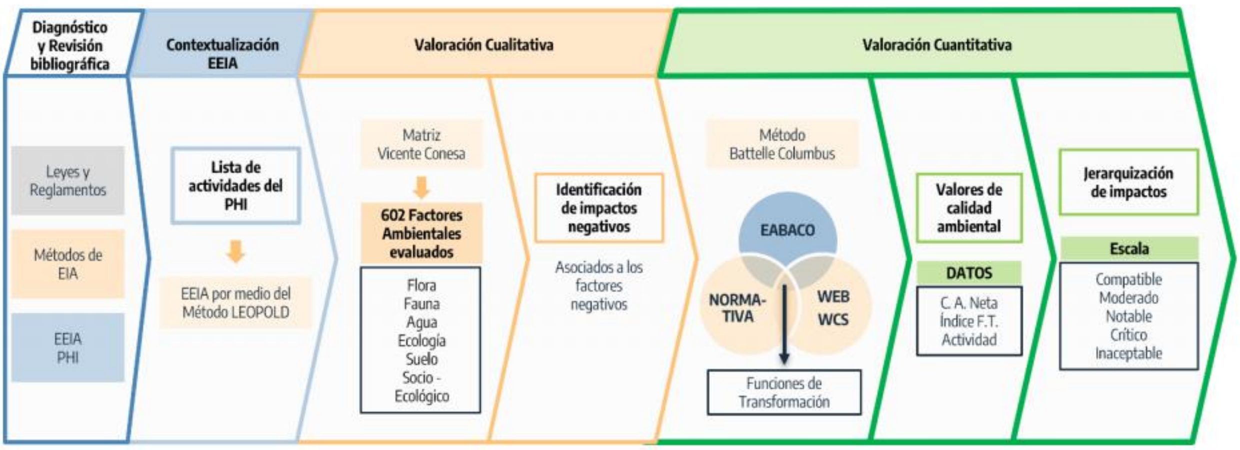


Figure 1. Methodological framework

2.1 Diagnosis and bibliographic review

It starts with a review and analysis of results and information recorded in the Environmental Impact Assessment Study - EIA of the project under study, responding to the environmental legislation in reference to the EIA of hydroelectric projects, which are also located on protected areas, to subsequently determine the activities and socio-environmental impacts associated with the project under study during the life cycle. This analysis is carried out according to the qualitative assessment recorded in the project's Environmental Record - FA, which categorizes it as "Category 1 Level: Comprehensive Analytical Environmental Impact Assessment Study". Due to the degree of incidence of effects on the system, its studies should include a detailed analysis and evaluation of all the factors of the environmental system: physical, biological, socioeconomic, cultural, legal-institutional, in order to determine activities and environmental factors that are prone to degradation based on current regulations.

2.2 Environmental contextualization of the case study project

Based on the identification of project activities and environmental factors, the CAUSE - EFFECT identification matrix is formed by determining the socio-environmental impacts associated with project activities, constituting parameters that serve as information tools for the evaluation of the environmental consequences derived from social and economic activities, affirming that an ecosystem is healthy if it is active and maintains its organization and autonomy over time and its buffering capacity (Bittermann & Haberl, 1998; Costanza 1992), so the study initially identifies as potential bioindicators of socio-environmental impacts, the valuation of ecosystems, expressed in loss of vegetation cover, fragmentation of plant communities, disturbance of particular species, among others, and that represent an impact on the different biogeographic units that converge in the study area.

2.3 Qualitative assessment of environmental impacts

Given that Bolivian regulations make explicit the environmental attributes related to the physical, abiotic, biotic and socioeconomic components, a qualitative assessment is made of all the impacts identified in the Leopold matrix, which represent the EIA of the project under study, proceeding to evaluate their socio-environmental impact by applying the matrix method of Conesa V. (2009), the same method used in the project's EEIA, which contrasts and determines the valuation of the socio-environmental impacts directly and indirectly affected by the project's activities.

2.4 Quantitative assessment of environmental impacts identified as relevant

It is developed for the environmental factors that were identified in the qualitative assessment as relevant because they generate an impact considered as negative for the environment. In the definition of the methodology, the Bartle-Columbus (1972) methodology was used. The environmental factors identified as mainly affected were evaluated through the use of the TF transformation function. and assessed through technical criteria adapted to these parameters, according to the indices established in the TF by Bolivian legislation, and the results obtained from GIS WEB (2019), a platform for mitigation hierarchy in terms of biodiversity.

2.5 Use of EABACO software

The tool efficiently applies the Battelle-Columbus method and evaluates the socio-environmental impacts generated by the project to determine its global environmental feasibility, interpret in the framework of energy sustainability and represent a real condition of interaction between nature and human society, with special emphasis on the spatial (local) aspects and the inclusion of short and long term perspectives, which constitute product evidence and are the result of the methodology used.

Methodology applied to the case study presents the following results:

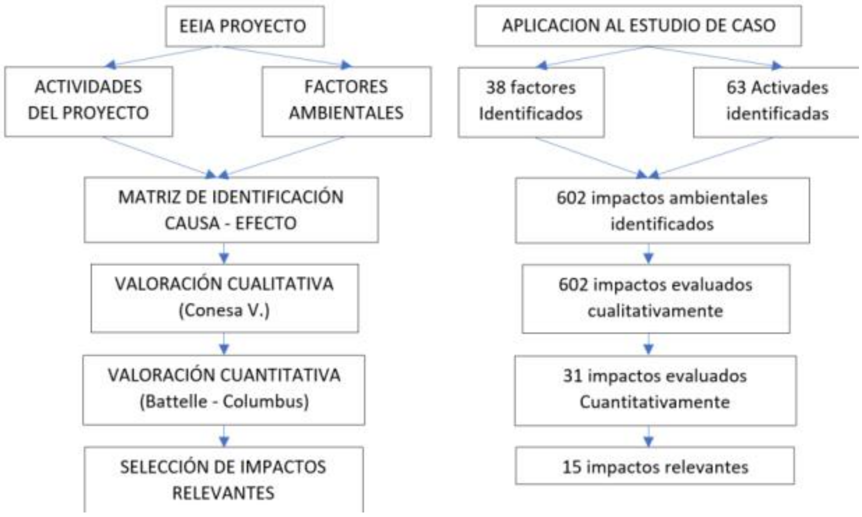


Figure 2. Results associated with the methodological process

3 Results and discussion

As a result of the appraisal of the EIA of the project under case study, it is determined that: i) It complies with the theoretical and methodological procedure and the provisions of the Environmental Law No. 1333, as well as the Protected Areas Regulations, and is endorsed by Law No. 819, which declares the implementation of the hydroelectric project to be of national interest and priority. ii) It is established that the 63 activities of the project have a favorable and adverse impact on the receiving environment, of which forty-nine correspond to the execution stage, five to the operation stage, five to the maintenance stage and four to the induced future stage, iii) The study area comprises two geographically distinct zones, the first in the Carrasco National Park, (Category II according to the IUCN, whose purpose is the conservation and protection of ecosystems) classified as Permanent Forest Production lands, where the hydraulic works of the project are established and include two basins, whose minimum ecological flows determined by the EEIA are 1.39 m^3/s for the dam and 1.65 m^3/s for the second intake; iv) Biogeographically, the project's area of intervention includes scrublands, grasslands, dry inter-Andean forests, Yungas montane forests and sub-Andean hyper-humid forests that extend from 4000-1000 m above sea level.

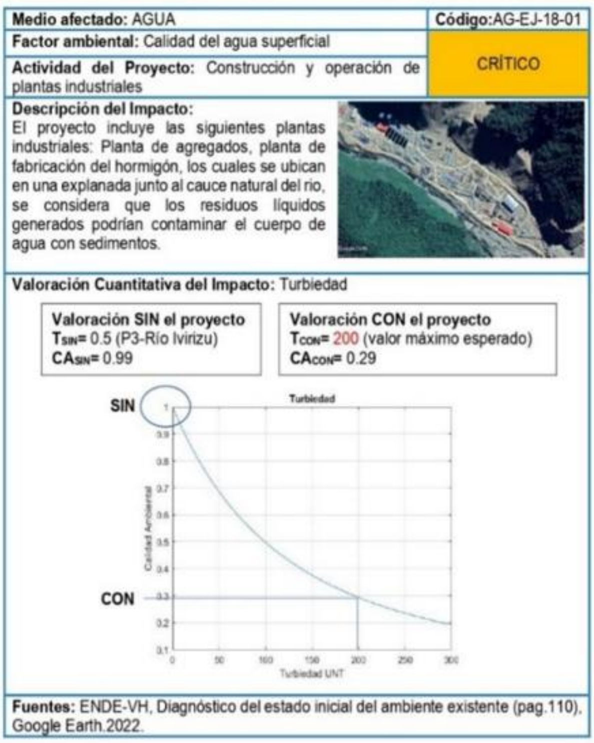
The EIA of the project under study begins with the validation of the EEIA through the application of Leopold's qualitative matrix, which categorizes the project with category level No.1 and determines the implementation of a Comprehensive EEIA on environmental factors. Likewise, according to the results obtained in the implementation of this cause and effect matrix, it is concluded a priori that the factors related to biodiversity are the most susceptible to degradation. It should be noted that the methodology applies socio-environmental impact assessment methods, but since there is no displacement of populations and the project is located in a protected area, it is not possible to assess the environmental impacts of the project. The results of the valuation applied to the case study, which as part of an initial diagnosis identifies 38 environmental aspects associated with environmental factors and relates them to the 63 component activities of the project for all its stages, and which are evaluated qualitatively, showing that the project does not represent a negative impact on the socioeconomic factor, as reflected in the results of the valuation applied to the case study.

In accordance with the proposed methodology and as a result of the qualitative assessment, the project activities that produce the greatest environmental impacts are identified and will be analyzed qualitatively and in greater detail at a later date. This assessment stage differs from the one presented in the EIAE because it is applied with greater emphasis on the impact-generating activities, concluding that the presence of the dam and the activities related to its consolidation are the sources that cause negative impacts, as shown in Figure 3.

Figure 3. Project activities with a priority impact on the environment

Likewise, prior to the quantitative assessment, we proceeded to identify the transformation functions that correspond to the impact-generating activities in the previous table, such as the filling of vessels and others, applying results from the GISWEB-WCS PLATAFORMA JERARQUIA DE MITIGACIÓN report (arcgis.com) for biodiversity aspects and specific regulations for the other factors. Table 1 summarizes the priority outcomes of factors related to biodiversity.

Table 1. Summary of results of transformation functions


Medio afectado: AGUA | **Código:** AG-EJ-18-01

Factor ambiental: Calidad del agua superficial | CRÍTICO

Actividad del Proyecto: Construcción y operación de plantas industriales

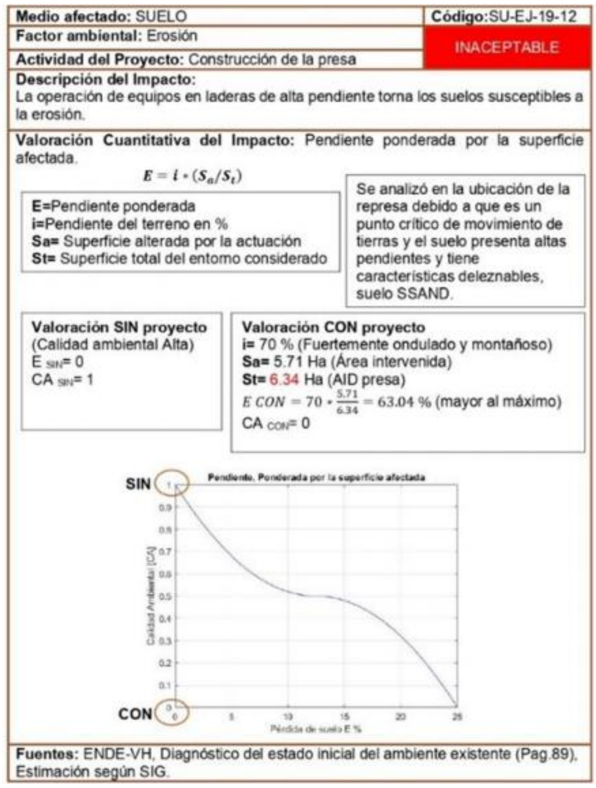
Descripción del Impacto: El proyecto incluye las siguientes plantas industriales: Planta de agregados, planta de fabricación del hormigón, los cuales se ubican en una explanada junto al cauce natural del rio, se considera que los residuos líquidos generados podrían contaminar el cuerpo de agua con sedimentos.

Valoración Cuantitativa del Impacto: Turbiedad

Valoración SIN el proyecto
T_{SIN}= 0.5 (P3-Río Ivirizu)
CA_{SIN}= 0.99

Valoración CON el proyecto
T_{CON}= 200 (valor máximo esperado)
CA_{CON}= 0.29

Fuentes: ENDE-VH, Diagnóstico del estado inicial del ambiente existente (pag.110), Google Earth 2022.


Medio afectado: SUELO | **Código:** SU-EJ-19-12

Factor ambiental: Erosión | INACEPTABLE

Actividad del Proyecto: Construcción de la presa

Descripción del Impacto: La operación de equipos en laderas de alta pendiente torna los suelos susceptibles a la erosión.

Valoración Cuantitativa del Impacto: Pendiente ponderada por la superficie afectada.

$$E = i * (S_a/S_t)$$

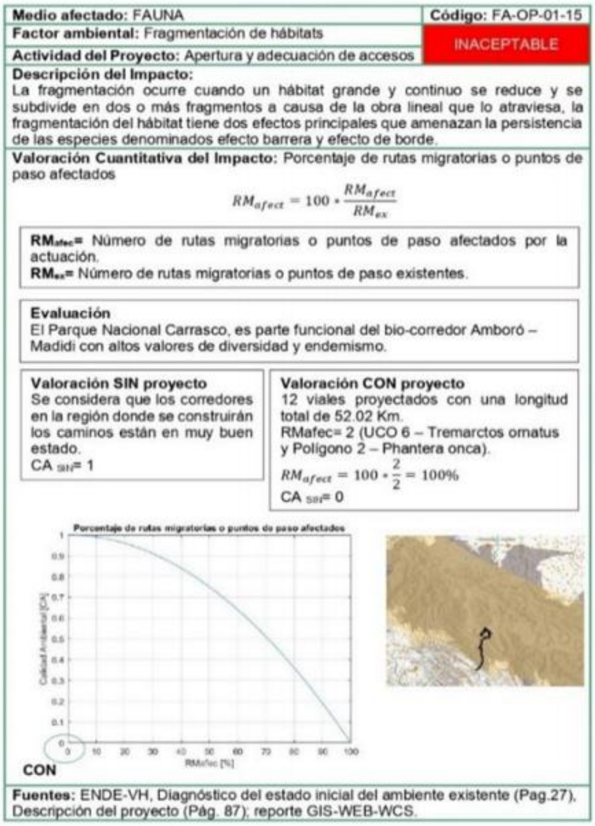
E=Pendiente ponderada
i=Pendiente del terreno en %
Sa= Superficie alterada por la actuación
St= Superficie total del entorno considerado

Se analizó en la ubicación de la represa debido a que es un punto crítico de movimiento de tierras y el suelo presenta altas pendientes y tiene características deleznables, suelo SSAND.

Valoración SIN proyecto (Calidad ambiental Alta)
E_{SIN}= 0
CA_{SIN}= 1

Valoración CON proyecto
i= 70 % (Fuertemente ondulado y montañoso)
Sa= 5.71 Ha (Área intervenida)
St= 6.34 Ha (AID presa)
$E\ CON = 70 * \frac{5.71}{6.34} = 63.04$ % (mayor al máximo)
CA_{CON}= 0

Fuentes: ENDE-VH, Diagnóstico del estado inicial del ambiente existente (Pag.89), Estimación según SIG.



For the quantitative valuation, the Battelle - Columbus (1972) method is used, adapted to Bolivian regulations and based on the indexes established for the transformation functions. We proceed to calculate the Net Environmental Quality - C.A. NETA, that allow us to rank the environmental impacts through the categorization of the values obtained according to the following scale: compatible impact: does not require actions to be mitigated; moderate impact: requires prevention actions; notable impact: In addition to prevention measures, it requires other levels of mitigation such as minimization and restoration; critical impact: It is very likely to require all levels of mitigation. (avoidance, minimization, restoration and compensation) and unacceptable impact: It represents a level that cannot be completely mitigated, even applying all possible levels of mitigation and therefore implies imminent loss of the resource. The hierarchy is based on the activities identified as generating negative impacts, the results of which are summarized in Table 2.

It should be noted that the analysis prioritizes the negative environmental impacts, rather than the impacts ranked as compatible or moderate, which require prevention actions and are part of the EEIA of the case study project, through the implementation of flora rescue plans and others that are being reported in the Environmental Monitoring Reports - EMR, as required by law, for the project execution stage.

Table 2. Ranking of environmental impacts susceptible to degradation

Ranking of Environmental Impacts					
Environmental factors and associated impacts		C.A. NETA	Index	Ranking hierarchy	Activity
	Removal of tree species	-36.5	Weighted percentage of covered surface area	Unacceptable	Deforestation of the basin
	Loss of vegetation cover	-32.41	Weighted percentage of covered surface area	Unacceptable	Deforestation of the basin

Flora	Disturbance of particular species (Flora)	-36.35	Variation in the relative number of protected species weighted by their importance	Unacceptable	Deforestation of the basin
	Fragmentation of plant communities	-38	Relative number of plant species affected	Unacceptable	Filling of the vessel
Fauna	Herpetofauna	-29.8	Variation in the relative number of protected species	Unacceptable	Deforestation of the basin
	Mastofauna	-24.65	Variation in the relative number of protected species	Unacceptable	Deforestation of the basin
	Disturbance of particular species (Fauna)	-19.84	Variation in the relative number of protected species	Unacceptable	Deforestation of the basin
	Avifauna	-24.66	Variation in the relative number of protected species	Unacceptable	Filling of the vessel
	Wildlife mortality	-12.8	Relative number of species of animals affected	Critical	Filling of the vessel
	Habitat fragmentation	-20	Percentage of affected migratory routes or crossing points	Unacceptable	Opening and adaptation of roads
Landscape	Visual intrusion	-26.5	Landscape quality	Critical	Construction of the dam
	Loss of characteristic landscape elements	-37.33	Average landscape quality weighted by surface area	Unacceptable	Deforestation of the vessel
Water	Flow variation	-33.22	Amount of the resource with respect to the total	Unacceptable	Filling of the vessel
Ecology	Impact on ecosystems	-32.28	Percentage of area affected	Critical	Filling of the vessel
Soil	Soil erosion	-23	Slope weighted by affected area	Unacceptable	Construction of the dam

Source: Own elaboration, August 2022.

The impact assessment was graded based on the results, and the conclusion was drawn that it had a critical impact on the biodiversity of the affected ecosystem. Therefore, monitoring and control are carried out based on indices that determine the percentage of weighted surface area covered, relative changes in protected species, and relative numbers of affected animal and plant species. Currently, mitigation measures at all levels are commonly adopted. In addition, it has been determined that most of the biological and ecological factors affecting biodiversity and ecosystems in the intervention area cannot be fully alleviated. In relation to the water and soil factors, the environmental impacts will be translated into variations in water flow in the river basins and soil eutrophication. Quantitative assessments classify these aspects as citric, which are related to the impact of climate change. Therefore, priority must be given to environmental monitoring and surveillance at different stages of the project.

Regarding the implementation of EABACO software, the report states that the overall impact level of the project is: a significant assessment of intermediate feasibility. Based on the weight of the method, it is close to infeasible, www.eabaco.org/in terms of environmental factors, and the product of the number of unacceptable and critical impacts on biological environmental factors. This fact clearly reflects the impact on the national park category protected areas (NPC), which is a general warning signal urging the promotion of research in the direct impact areas of the project, in order to more accurately quantify the impact on the ecosystem by considering the mitigation measures proposed by the project, and evaluate whether these measures are sufficient to be included in the environmental monitoring report - IMAS, Legal provisions.

The results obtained from EABACO allow for the creation of a habitat quality map that overlaps with the project AID area, based on cumulative impact assessments obtained in percentages (only for critical and unacceptable impacts) and project components, in contrast to the overall quantitative assessment of the project obtained from EABACO software, and generate a weight of -596.77 (for important mid-term environmental feasibility projects). This value represents 100% of the impact of the analysis, and it was found that the greatest environmental impact occurs in higher quality ecosystems at altitudes ranging from 1000 to 1500 meters, corresponding to the project reservoir area. (Figure 4)

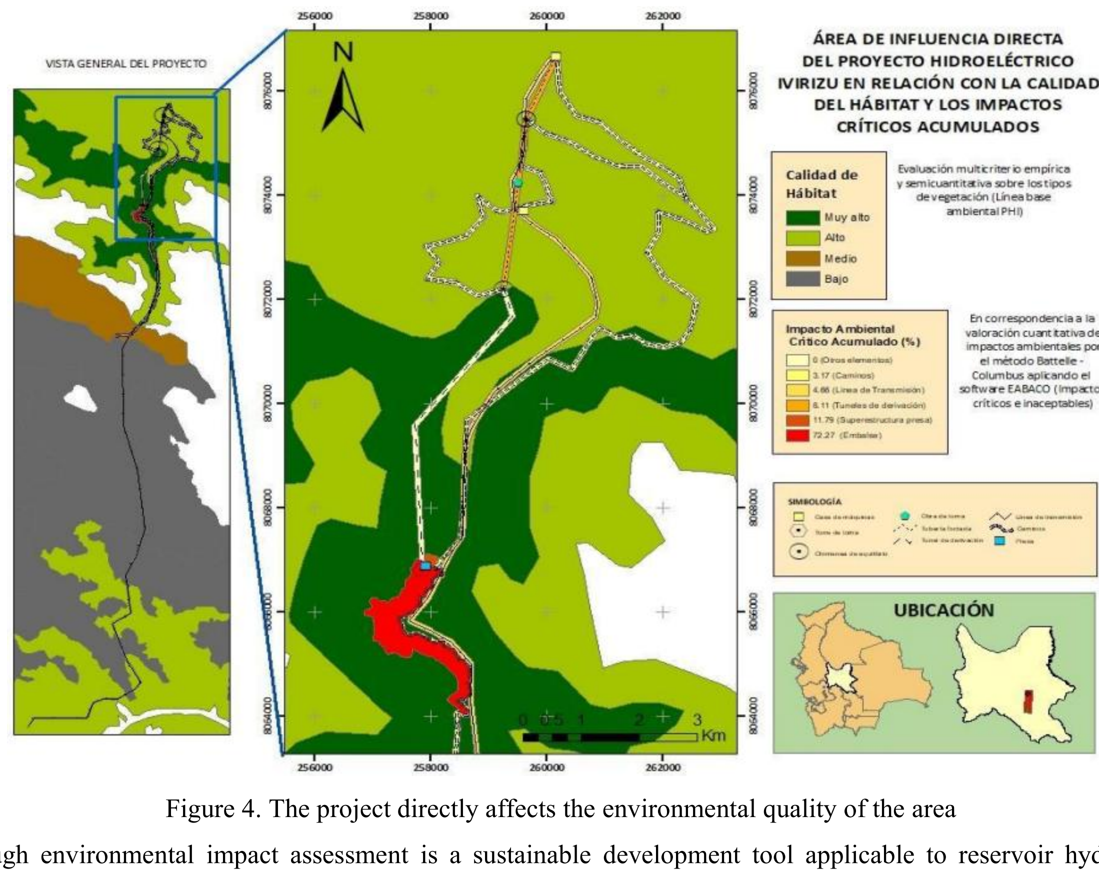


Figure 4. The project directly affects the environmental quality of the area

Although environmental impact assessment is a sustainable development tool applicable to reservoir hydropower projects, it can be seen that its implementation has not achieved the expected sustainable development. However, by preliminarily classifying the impacts generated by these projects, it can have an impact on specific actions to appropriately mitigate the related impacts. Under this premise, it is crucial to classify the initial conditions for the protection status of the ecosystem to be intervened in order to ensure the environmental sustainability of reservoir hydropower projects. This is because when determining the social and environmental impacts, environmental factors that are usually particularly affected are specifically quantified. As emphasized in this study, projects located in mountainous areas will not lead to population displacement, but the presence of reservoirs makes them critical, despite the geomorphic features of mountainous ecosystems. In addition, due to the different altitude gradients and biogeographic regions involved in these projects, which are composed of the unique flora and fauna diversity of these spaces. It is necessary to include specific research on species biological corridors and environmental protection areas to ensure the quality of the intervened habitats. This is a continuous condition for most hydropower project environmental impact assessments, regardless of the ecosystem being intervened in.

Another aspect that needs to be emphasized is that although this is not a multi-purpose project, it is designed through endogenous development, as it contributes to energy security and equitable access to electricity for upstream Andean communities within the framework of energy sustainability

4 Conclusion

The research results indicate that it is possible to classify the environmental impacts of hydropower projects established in mountainous areas and adopt different environmental impact assessment methods, which come from the procedures stipulated by environmental laws and allow for comprehensive assessment within the framework of environmental and energy sustainability.

When assessing environmental impacts based on the specificity of the environment to be intervened in, the application of different environmental impact assessment methods is limited and inappropriate, as these methods focus on demonstrating the overall environmental feasibility of the project. It is necessary to specify these impacts. The transformation function, which has developed into a core element of the hierarchical system, effectively helps to determine the overall environmental feasibility of the project by quantitatively assessing the environmental impacts identified as negative based on priority information, rather than ineffective implementation of methods and practices applied to environmental impact assessment.

On the other hand, it involves studying baselines isolated by environmental factors rather than through national policies or other case study guidelines related to biodiversity conservation, which go beyond regulatory compliance corresponding to these assumptions. This creates greater uncertainty and leads to the conclusion that biodiversity is underrepresented in the International Space Station. They have a negative impact on proposed mitigation, ecological restoration, or environmental adaptation measures, and priority should be given to developing control and/or monitoring tools for rescue plans of animals, plants, and other species as part of IMAS.

The use of geographic information systems (GIS) in the design phase of reservoir hydropower projects is crucial for determining baselines for intervening in ecosystem biodiversity. In this case study, it was implemented through the GIS Web Cs mitigation hierarchy platform and applied to aid areas (reservoir areas, transmission lines, roads, and channels). Therefore, by seeking "zero net loss", the impact on ecosystems and identified endemic and/or threatened species was more accurately assessed. This represents the correct application of the concept of environmental mitigation hierarchy within the framework of environmental sustainability, which is why the initial and specific classification of environmental impacts in the project site area effectively promotes the environmental sustainability of the intervened ecosystem. It is necessary to classify the social and environmental impacts from the design stage of hydropower projects as a measure to achieve affordable, safe, and sustainable energy that is commensurate with the country's sustainable energy development.

Conflicts of interest

The author declares no conflicts of interest regarding the publication of this paper.

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