

Article

Design of a Green Corridor and the Revitalization of the Huatanay River, City of Cuzco, Peru—2024

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Abstract: Population growth in the last 30 years has generated an energy shortage and excessive consumption of products, generating a large percentage of solid waste. Urban expansion has led to a significant impact on the biodiversity of both flora and fauna. In this context, the objective of this research is to develop a design for a green corridor that optimizes ecological energy efficiency and contributes to the revaluation of the Huatanay River in Cuzco. The methodology used in this study is articulated in four stages: literature analysis; analysis of the environment through supporting data such as Climate consultant, SIGRID, and GEO Peru; results where the proposed project is carried out; and finally, the conclusions and discussions where they are contrasted with a similar bibliography. The design of the green corridor efficiently takes advantage of the natural resources available in the area, which has 70% green areas and 30% public spaces, where 13 kWh/day of energy is generated, according to the calculations made in sector 2 of the botanical garden that will later be replicated in the other sectors, derived from biodigesters for the lighting of spaces of the botanical garden. The corridor, in turn, aims to recover the ecological function of the river through the restoration of its course, the reforestation of its banks, and the creation of recreational areas. In conclusion, the green corridor aims to revitalize the Huatanay River through different elements, among which the botanical garden stands out.



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Keywords: green corridor; social connectivity; revitalization; Huatanay River

1. Introduction

Currently, the world population has reached around 8 billion people, marking a notable increase compared to the approximately 2 billion people about a hundred years ago. The inevitable rise in urbanization and the decline in urban quality of life over the past few years has driven the development of sustainability in cities. For this reason, compact cities with high population densities are opting for the creation of green spaces, which complement residential areas as a means of fostering human interaction. This is because cities today are expanding exponentially without any proper planning, leading to a false development of green areas and, consequently, a decline in people's quality of life, as the minimum requirements for living a fulfilling life are not being met [1,2].

Globally, river ecosystems have historically been affected by urban expansion, industrial development, and deforestation, factors that contribute to their environmental degradation and loss of capacity to provide key ecosystem services, such as water purification, flood regulation, and biodiversity maintenance [3,4]. Cities like London, Seoul, and New York have faced similar challenges with their bodies of water, which has led to large-scale regeneration projects that include the creation of green corridors, river restoration, and the strengthening of ecological infrastructure [5]. Figure 1 shows the Thames River in London, which went from being one of the most polluted rivers in Europe due to industrial waste and sewage to becoming a model of ecological revitalization thanks to a series of

conservation and sanitation projects [6]. One of the projects is the Tideway Project, which aims to build an underground tunnel along the Thames to prevent the sewer system from discharging wastewater during heavy rains. The completion of this project is expected by 2025 [7,8]. Similarly, the Cheonggyecheon River project in Seoul transformed a highway into a green corridor, removing 3.6 km of road infrastructure, and building linear parks and pathways along the restored river's course. This corridor was not only designed for pedestrian and recreational transit but also to enhance ecological connectivity within Seoul, improving water quality, biodiversity, and the well-being of the urban population [9,10].



Figure 1. The references are (a) River Thames, the longest in England, reprinted with permission from [11], 2021, Fundación Aquae; (b) Cheonggyecheon Restoration Project, reprinted with permission from [12], 2021, Harvard University.

The success of the projects has led to growing global recognition of the importance of incorporating green corridors into urban planning. Green corridors not only connect fragments of natural habitats but also offer social, recreational, and climatic benefits by functioning as “lungs” for cities, mitigating urban heat islands, and creating recreational spaces for communities [13,14]. These initiatives align with a sustainable development approach that aims to restore harmony between nature and urban environments, fostering city resilience in the face of challenges such as climate change and biodiversity loss [15].

Public spaces enable interaction between users and nature, creating opportunities for greater connectivity. Additionally, the frequency of social interaction in green areas is a factor that strengthens community attachment and resident relationships, and it even has positive effects on people's health [16]. This same social interaction considers the accessibility of urban green spaces as a cornerstone for advancing urban sustainability [17]. Thus, it fosters an approach that ensures the balanced use of resources to guarantee the long-term viability of the urban environment, human development, and advances in environmental perspectives and related issues. It incorporates human environmental variables into the traditional urban environment vision and focuses on institutional, economic, and social organization [18,19].

In Latin America, the situation of urban rivers is particularly critical due to rapid urbanization and inadequate planning concerning water resource management [20]. Rivers such as the Bogotá in Colombia, Mapocho in Santiago, Chile, and Rímac in Peru face severe pollution and deterioration issues, impacting both ecosystems and public health [21]. Figure 2 illustrates the main activities that pollute these rivers, highlighting mining, agriculture, household waste, and industrial waste in all three cases. In this context, river restoration through the design of green corridors has been proposed as a comprehensive solution, with the potential to improve water quality, increase biodiversity, and restore the scenic value of these areas. A notable example is the Mapocho River in Santiago, Chile, where the construction of riverside parks has contributed to its ecological rehabilitation and created recreational spaces for residents [22,23].

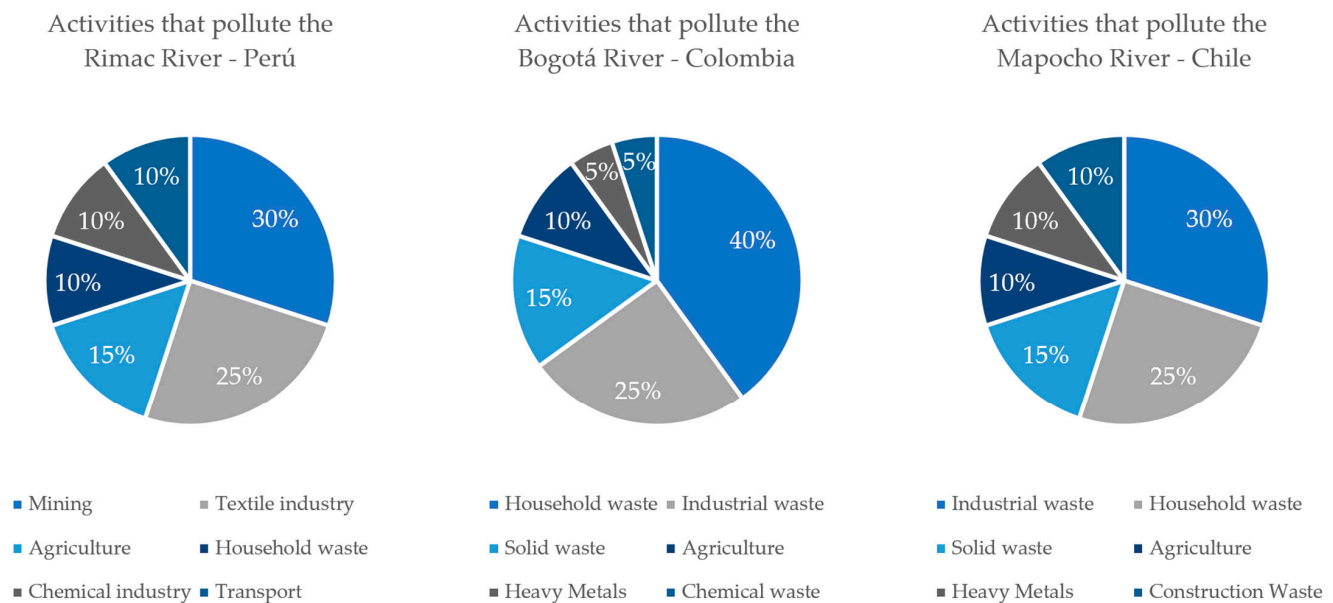


Figure 2. Activities that pollute rivers in different countries.

The case of the Huatanay River in the city of Cuzco presents a similar issue. This river, which was once a vital source for the city, has been severely impacted by pollution, urban encroachment, and a lack of effective environmental policies. As shown in Figure 3, urban population growth has increased pressure on its banks, leading to a loss of its natural ability to maintain good water quality and support native species [24–26].



Figure 3. Evolution of the population in the city of Cuzco.

Cuzco currently has a population of 1,316,729 residents, making it one of the nine most populated cities in Peru [27]. Its growth over the years has been inconsistent, with a tendency to expand eastward, reaching its current size of 385.1 km². This growth has also positioned Cuzco as one of the most visited cities by tourists, due to its numerous natural and cultural attractions. Figure 4 shows the influx of both foreign and domestic visitors to Cuzco over the years, with 65% being foreign tourists and 35% domestic tourists up to 2023 [28,29]. The population increase has highlighted the shortage of accessible green spaces in the urban area, creating an urgent need for ecological infrastructure that not only facilitates environmental regeneration but also provides recreational and social benefits to Cuzco's residents [30].

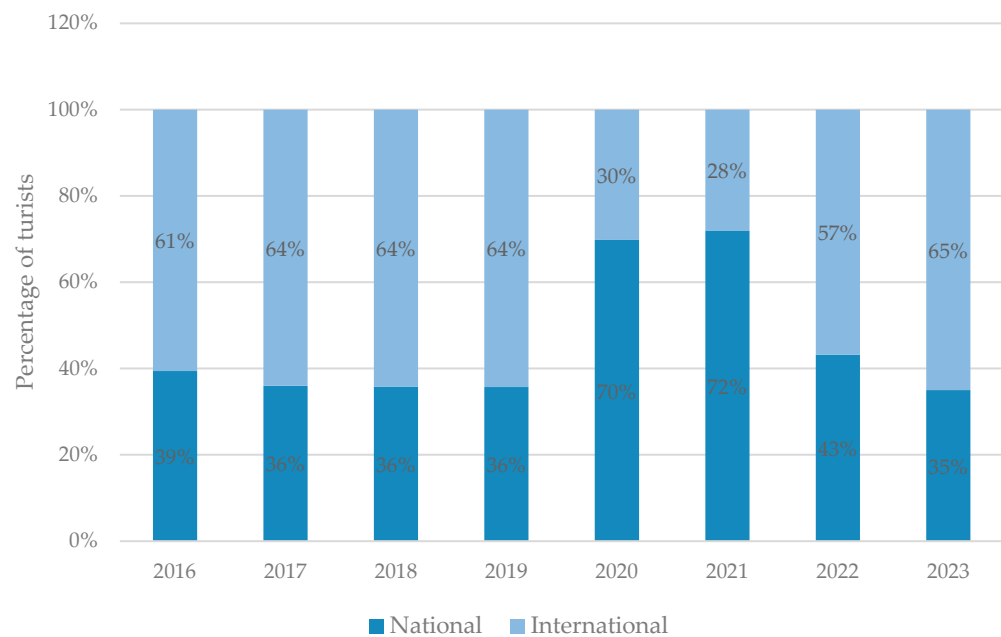


Figure 4. Comparison between national and international tourists.

In response to this situation, the proposal to design a green corridor along the Huatanay River emerges as a comprehensive solution aimed at restoring its ecosystem, improving the connectivity of green spaces in the city, and revaluing the urban landscape. This initiative aims to recover the ecological function of the river through the restoration of its course, reforestation of its banks, and creation of recreational areas, which will contribute to enhancing the quality of life for residents and fostering a more sustainable relationship between the city and its natural environment. By following successful river regeneration models implemented elsewhere in the world, this research aims to propose the design of a green corridor for the revitalization of the Huatanay River in Cuzco.

2. Materials and Methods

2.1. Methodological Scheme

Figure 5 shows the methodological scheme, which breaks down the research into 4 stages. The first stage consists of the analysis of the literature, through which it seeks to raise and develop the problem found in the region, pointing out dimensions and indicators. The second stage consists of the landscape analysis, where through support data such as climate consultant, SIGRID, and GEO Peru, we seek to define the terrain within the place of study, supported by graphs and maps that allow us to understand the context of the city at an environmental and urban level. The third stage is the results stage, where through the development of the 2 previous stages the proposed project is carried out through an urban element supported by different design strategies that focus on the revitalization of the river. Finally, the fourth stage consists of conclusions and discussions where the results contrast the data obtained with a similar bibliography, highlighting similarities and differences and then listing the conclusions of the project.

This research is non-experimental, starting with the collection of information from scientific articles and then identifying and classifying data relevant to the topic. Finally, appropriate design strategies are applied to develop a proposal that meets the intended goals.

Figure 6 shows the process by which the proposal will be developed in a coherent manner, taking the revitalization of the Huatanay River as its axis. As a first step, we have the site analysis. Through tools such as Google Earth, we obtain information that will be of utmost importance in the design of the corridor, such as topography or urban elevations. The second step consists of the conceptualization of the idea of the corridor. This is to generate new connections or axes that provide dynamism to the space contemplated.

Subsequently, the third step consists of surveying the space in 3D software to understand how the project relates to its immediate environment, considering aspects such as the environment and climatology. Finally, as a fourth step, the analysis of the design strategies is considered. This is to highlight how they affect the revaluation of the river. This is achieved through calculations and routes that allow us to gain a dynamic understanding.

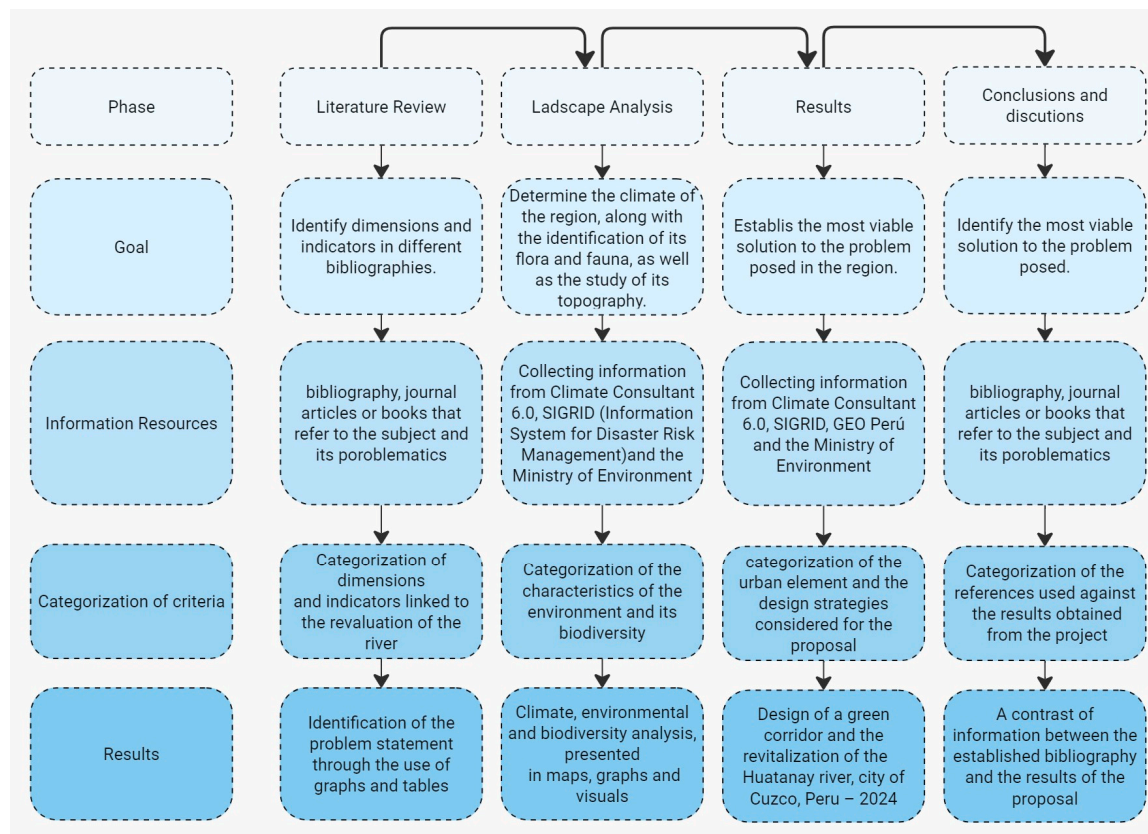


Figure 5. The methodological sequence applied in the project.

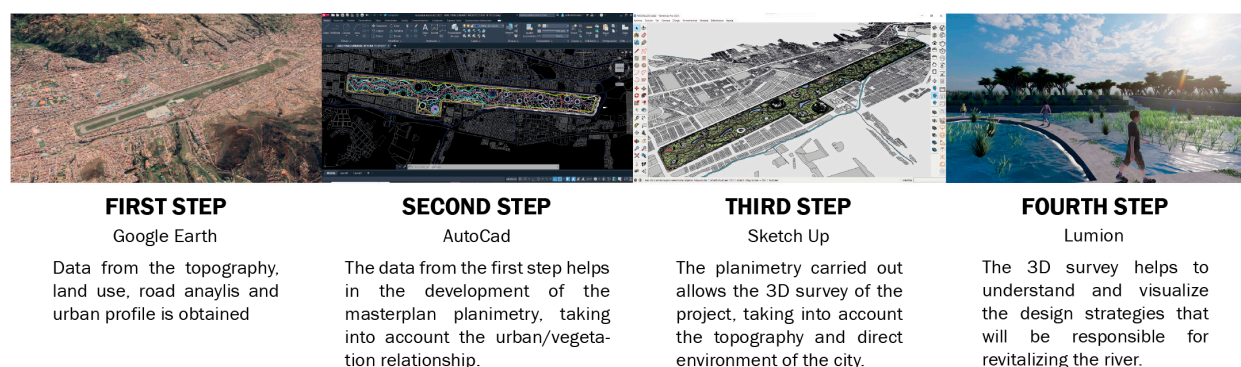


Figure 6. Steps for carrying out the proposal.

2.2. Place of Study

The city of Cuzco is located on the eastern slope of the Andes Mountain range, with an area of 385.1 km² and a current population of 437,538 inhabitants. Its historical importance dates to ancient civilizations, as it was the heart of the Tahuantinsuyo empire in the time of the Incas. This historical legacy not only contributes to its cultural value but also drives its relevance today as an important tourist and cultural center known for its impressive archaeological remains and its rich indigenous heritage. The combination of its rich history and its role in preserving Andean culture make Cuzco a place of great interest

and attraction for both researchers and visitors from around the world [31]. Figure 7 shows the geographical location of the area in which the intervention will take place, located in the city of Cuzco, which is distinguished by its historical relevance to the country and its Inca architecture [32].

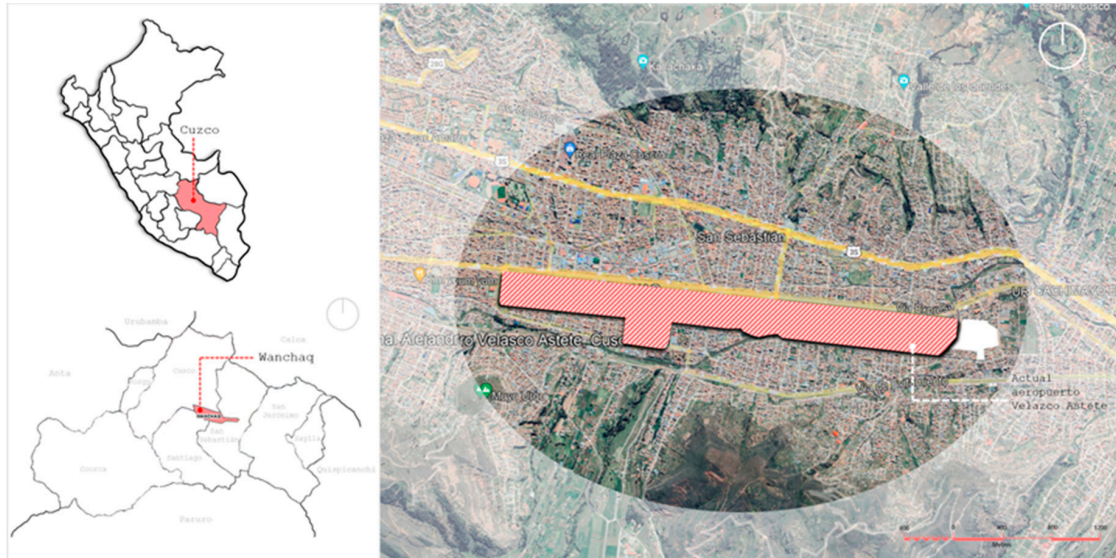


Figure 7. Location of the place of study.

2.2.1. Climatology

Cuzco is situated at an altitude of 3999 m above sea level, located in the mid-Andean zone. This means that its climate is predominantly semi-warm, with areas varying from semi-dry to rainy. Figure 8 shows the high and low levels of temperature and average humidity during the year, with the months of September and October reaching the highest temperatures and the month of July the coldest month, with humidity varying between 54% and 67% [33,34].

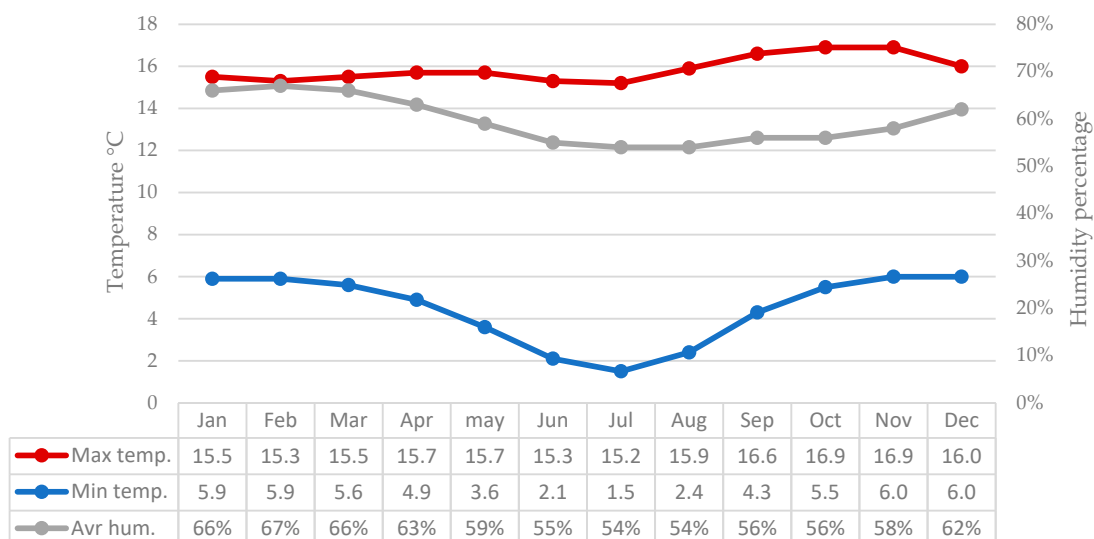


Figure 8. The diagram shows the annual climate of the city of Cuzco.

2.2.2. Flora

Cuzco exhibits a wide diversity of plants adapted to the cold and dry environment, some of which can withstand thermal fluctuations and last for centuries. The exact number of species is not known. In terms of orchids alone, approximately 420 species are found

in the Machu Picchu area. Figure 9 shows the distribution of some species in the city, like 1. Orchids (*Orchidaceae*), 2. Molle (*Schinus molle*), 3. Chilca (*Baccharis latifolia*), 4. Floripondium (*Brugmansia arborea*), 5. Puya raimondii (*Puya raimondii*), 6. Queñua (*Polylepis*), 7. Retama (*Retama sphaerocarpa* L.), 8. Cherimoya (*Chirimoyo*), 9. Ichu (*Stipa ichu*), and 10. Retamilla (*Genista monspessulana*) [35].



Figure 9. Distribution of flora in the city of Cuzco.

2.2.3. Fauna

The local fauna, favored by the excellent conservation of the plant formations, displays a remarkable variety of species. A total of 13 species of fish, 12 species of amphibians, 22 species of reptiles, 423 species of birds, and 53 species of mammals have been identified in the area. This diversity reflects the ecological health of the environment, providing suitable habitats for a wide range of organisms. Figure 10 shows the distribution of some species in the city of Cuzco, like Guinea Pig (*Cavia porcellu*), 2. Andean puma (*Puma concolor*), 3. Llama (*Lama glama*), 4. Andean Condor (*Vultur gryphus*), 5. Oso de anteojos (*Tremarctos ornatus*), 6. Alpaca (*Vicugna pacos*), 7. Vicuña (*Vicugna vicugna*), 8. Gallito de las rocas (*Rupicola peruviana*), 9. Tropical house gecko (*Hemidactylus mabouia*), and 10. Wasp hunting tarantulas (*Pesini*) [36].



Figure 10. Distribution of fauna in the city of Cuzco.

3. Results and Discussion

3.1. Project Location

Figure 11 shows that the area chosen for the development of the project is situated in the area where the Velazco Astete International Airport is currently located. From a feasibility standpoint, the site is well connected by two main avenues: the Vía Expresa and Avenida Velazco Astete, which facilitates access. The 120-hectare plot of land has a rectangular shape and an almost-level topography, with an elevation variation of 50 m along a 7.8 km extension.



Figure 11. Limits of the terrain and principal roads.

The immediate surroundings of the land show a large percentage of medium-density homes, followed by local businesses (Figure 12). It should be noted that the use of the airport currently serves as an element that does not take into consideration its environment, so many of these homes or facilities tend not to be in a good state of conservation.

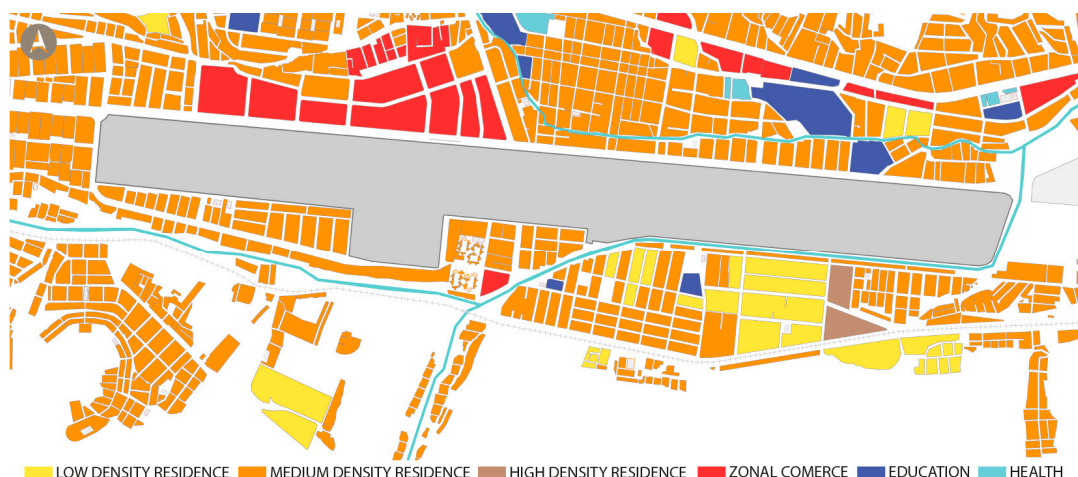


Figure 12. The maps show the land use in the city of Cuzco.

3.2. Masterplan Proposal

The development of a green corridor with a comprehensive and sustainable perspective is proposed to reduce the carbon footprint in the city of Cuzco, which is seriously affected by pollution derived from illegal mining and the deterioration of rivers due to abandonment and lack of maintenance. This project not only seeks to improve air quality and the natural environment but also to offer a comprehensive solution for waste manage-

ment and environmental regeneration. Figure 13 shows the division of the area into three differentiated zones: a cultural zone, a convention center, and a botanical garden.



Figure 13. Distribution of the master plan.

The convention center would be established as the main core, standing out for its ability to facilitate interaction and exchange between local residents and international visitors. The botanical garden, on the other hand, plays a crucial role in this project. Thanks to the integration of renewable energy technologies, such as biodigesters and biogas, it will become a self-sufficient and ecologically balanced space. In addition to providing a recreational and environmental education area for citizens, the botanical garden will contribute to the conservation of local biodiversity and the development of sustainable practices.

Botanical Garden

The botanical garden is divided into three sectors, each of which has a guinea pig farm that contributes to the production of energy for its respective sector. This innovative system allows the energy generated to be used sustainably throughout the garden. The sector also has other design strategies, such as terraces and biofilters, which together seek to purify and revitalize the Huatanay River. In addition, the space has various attractions and functional areas, such as a butterfly garden where visitors can observe different species of butterflies in their natural habitat, greenhouses that house a wide variety of exotic and native plants, and rest areas where people can relax. Designated areas for social interaction have also been created. This area will be subdivided into three sectors, which will present their own equipment and design strategies to make these spaces self-sustainable (Figure 14).

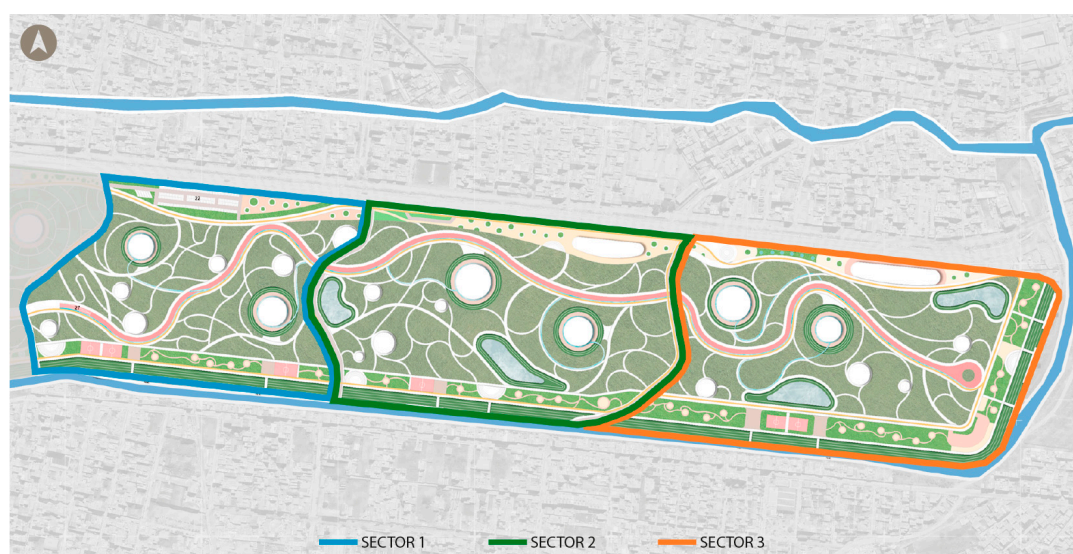


Figure 14. Distribution of the botanical garden.

Each sector of the botanical garden will have specific equipment to achieve the revitalization of the river, highlighting design strategies such as biodigesters, biofilters, and terraces. For practical purposes of the research, the calculations and subsequent views will be in sector 2 of the botanical garden, considering that these can be replicated and adapted to the other sectors to generate a uniform and circular system (Figure 15).



Figure 15. Urban equipment of sector 2.

3.3. Design Strategies

The design of the botanical garden is supported by different design strategies to generate a self-sufficient element that takes as its focus the revitalization of the river.

3.3.1. Biofilters

The biofilter is an excavated basin in which plants and sediments remove contaminants in the water, increasing its purity. They must have good filtering properties, absorption of contaminants, and the ability to transform contaminants by plants and associated microorganisms, allowing the removal of organic matter, nitrogen, metals, sediments, phosphorus, and pathogens. These are devices used for the removal of contaminants in the water and their contributing use in the master plan to clean the river for use in irrigating the green elements present [37]. Figure 16 shows one of the biofilters proposed in the project, these elements seek, through filtration and supported by different flora, the purification of the waters of the river to clean it and increase the lost channel.

Wastewater is characterized by elements that have undergone modifications that may make their consumption pose a risk to human health in general. Normally, its use is restricted to activities with low risk potential, such as certain industrial, domestic, and community applications. In the context of the proposed green corridor, the treatment of this water is essential since it acts as a continuous source of water. To address this need, alternative techniques, such as the implementation of artificial wetlands and advanced filtration systems, are contemplated [38]. These methods are designed to restore the river in an effective and environmentally friendly way, promoting sustainable and economic

management of the water resource. In addition, these techniques will not only contribute to the improvement of water quality but will also offer additional ecological benefits, such as the creation of habitats for various species and the strengthening of local ecosystems.



Figure 16. Distribution and use of biofilters.

The use of certain plants in biofilters is due to their natural properties, which make them effective for water filtration and improving air quality, especially in specific ecosystems. Figure 17 shows the Cantuta has the ability to absorb nutrients such as nitrates and phosphates from water. The Molle can develop in saline soils, and its leaves have antibacterial properties that reduce the bacterial load in the water. Chachacomo, with its roots, facilitates the filtration of suspended particles and the absorption of heavy metals, while Chilca is capable of accumulating metals such as cadmium and lead [39,40].

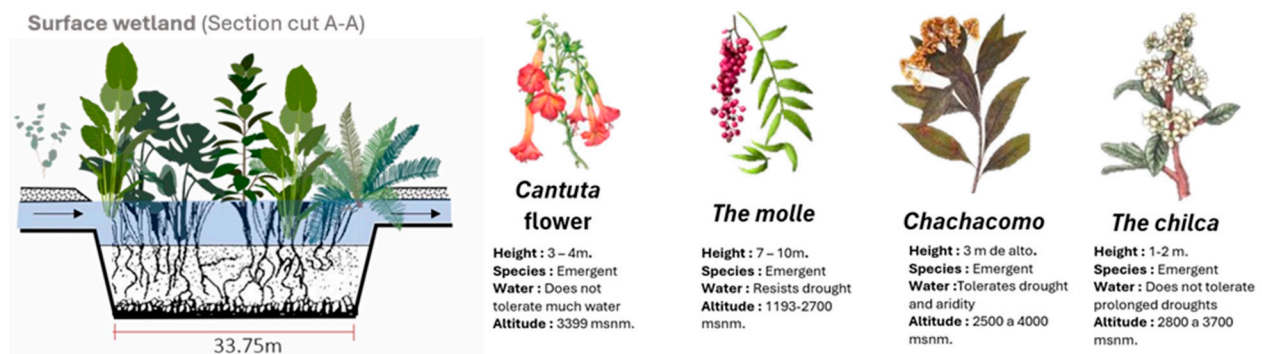


Figure 17. Flora used in biofilters.

3.3.2. Terraces

This experimental agricultural method, used in the Inca Empire and particularly in the Moray region, is based on a tiered design that takes advantage of groundwater. This system creates platforms with distinct microclimates, allowing the cultivation of a variety of plant species on each level [41]. The aim of the project is to integrate greenhouses and butterfly farms to develop specific microclimates. These diverse microclimates are intended to provide suitable conditions for species that cannot adapt to the general climate of the surrounding region. Figure 18 shows an example of the application of terraces as a design strategy for the revitalization of the river, through these systems, it is sought that the river adjoins the vegetation, generating a green strip directly related to the water body. It also functions as a kind of viewpoint on the strip that borders the garden, generating spaces for social interaction for users [42].



Figure 18. Distribution and use of terraces.

3.3.3. Biodigester

It is a closed organic waste treatment system that uses anaerobic biological processes to break down organic matter in the absence of oxygen. This digestion process produces biogas, a mixture of methane and carbon dioxide, which can be used as a renewable energy source, and biol, a nutrient-rich fertilizer that can be used to improve soil quality. Biodigesters are used in both agricultural and urban contexts for waste management and energy generation. This gas is a unique renewable energy source due to its versatility in energy applications. It can be used as a gaseous fuel for various uses, providing an efficient and sustainable alternative to fossil fuels. In addition, after processing, the waste resulting from gas production can be transformed into compost, a valuable resource for agriculture and gardening. This ability to use organic waste for both energy production and fertilizer generation underlines its importance in waste management and in promoting sustainable practices [43,44]. Figure 19 shows the biodigesters installed in the surroundings of the guinea pig farms, to speed up the feeding process of the system. And the process of obtaining energy using these systems is also observed schematically, from the raw material to the usable results.

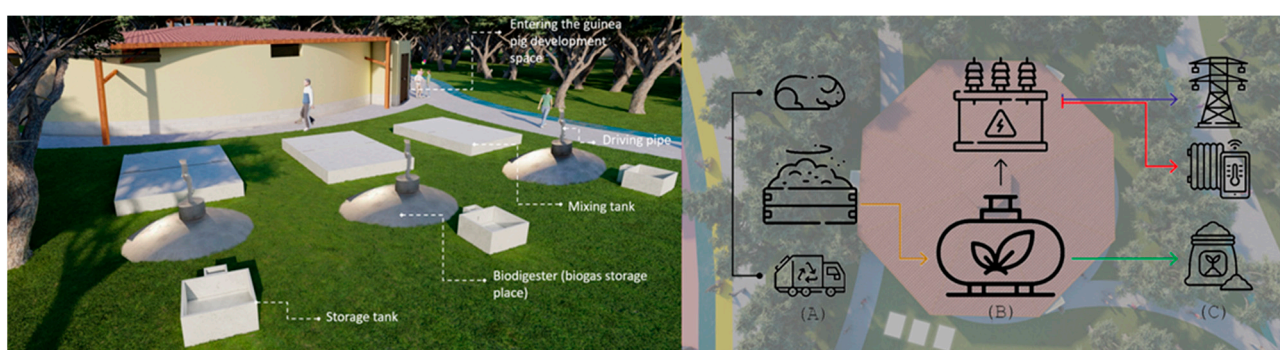


Figure 19. Distribution and use of biodigesters.

3.3.4. Guinea Pig Farms

In the design of the space for the development of the guinea pig, a hybrid space is proposed, where users can interact with the species, and they can develop and grow in the same place. This space will house the guinea pigs that will generate excrement that will be used to generate biogas that will be processed in the biodigester. Each of these will consist of three areas, the exhibition area has a system of terraced houses that will allow indirect user interaction, and then the breeding area is presented, where the guinea pigs will carry out mating activities to later be transferred to the exhibition areas. Finally, the

interaction areas are presented, where users will be able to have a more direct approach with the guinea pigs and be able to interact with them (Figure 20).

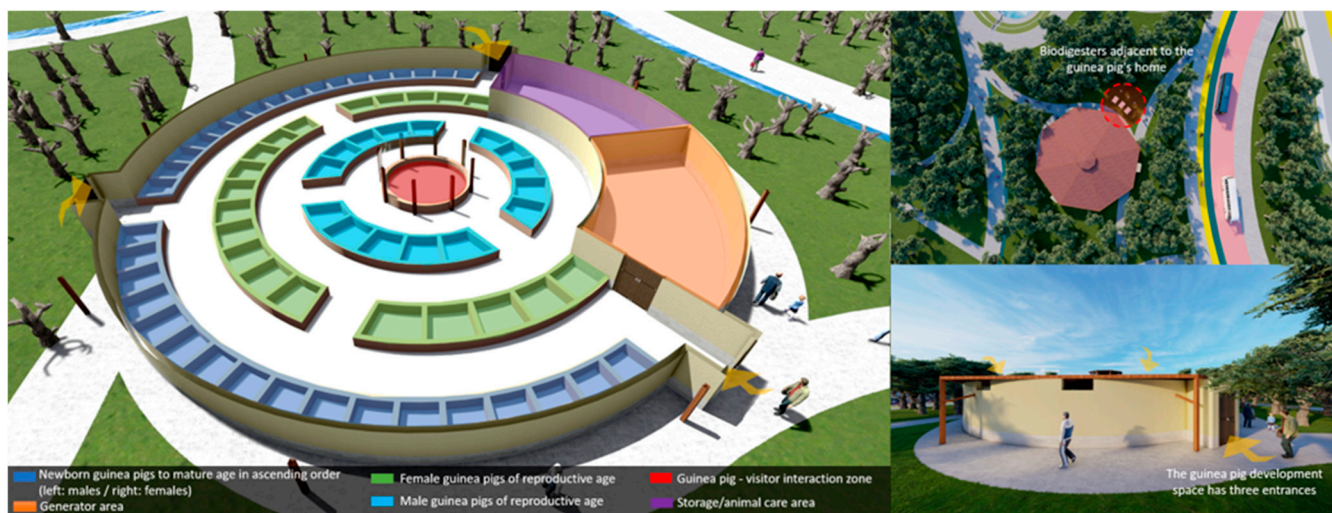


Figure 20. The distribution and architecture used for the guinea pig farms.

Design strategies include the use of sloping roofs to prevent rain and a double row of windows to generate good cross ventilation. Likewise, the building will have adobe walls with a thickness of 40 cm due to its thermal processing of $0.22 \text{ W}/(\text{m}^2\text{K})$, this will allow the space to be kept cool in the mornings and warm enough at night to have the guinea pigs in comfort. Figure 21 schematically shows the use of cross ventilation in the architecture of spaces for the development of guinea pigs as a design strategy.

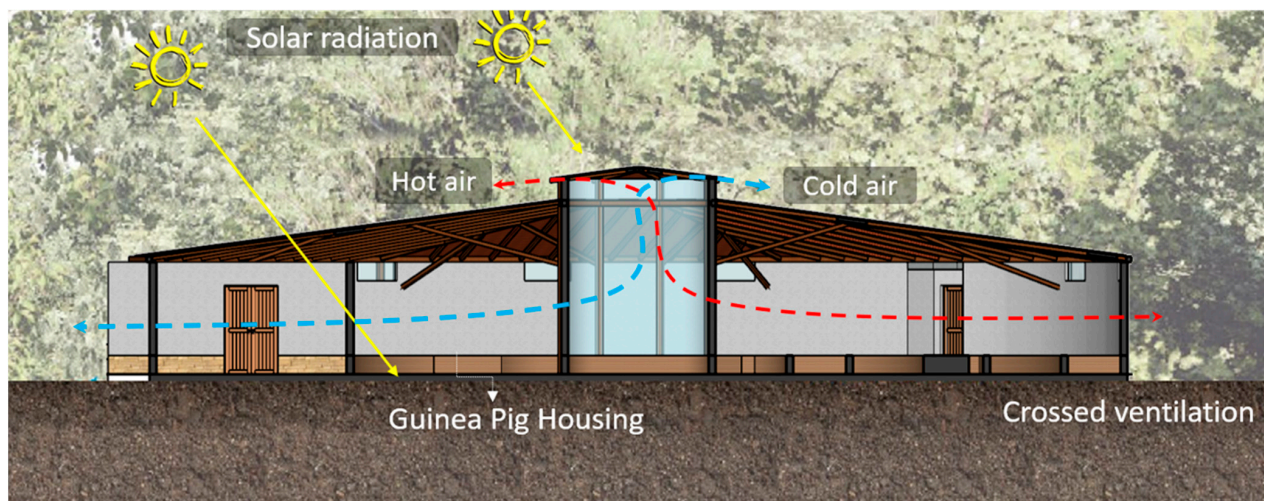


Figure 21. Section of the guinea pig farms that shows the use of cross ventilation in the architecture of spaces for the development of guinea pigs.

3.4. Calculation for Sector 2: An Example Case Study

Within the green corridor, the creation of a self-sustainable botanical garden is proposed, which will be helped by different biodigesters and guinea pig farms for the breeding and production of biogases and fertilizers, which are cyclically nourishing the different species located within. The use of guinea pigs is vital because their manure contains a high level of chemical components that allow for greater biogas production (Table 1). The use of these animals also contributes to a circular economy because they function as an attraction

for users, and it is proven that the consumption of their meat is beneficial for the body due to its high levels of protein and low levels of fat.

Table 1. Chemical composition of guinea pig manure.

Nutrients (ppm)	%
Nitrogen (N)	0.70
Phosphorus (P)	0.05
Potassium (K)	0.31
Ph	10

As mentioned, the area to be worked on will be sector 2. This is because it is the largest, and its results can be easily adapted to the neighboring sectors. In this sector, lanterns with a radius of 7.5 m were placed; therefore, the distance between lanterns will be 15 m in areas of greater influx and 30 m in areas of less affluence, gathering a total of 144 lanterns. Those considered will present LED lighting technology, due to its low energy consumption and high power, so the total energy demand per day would be 13 Kw/day (Figure 22).



Figure 22. The arrangement of the LED light posts in sector 2.

Table 2 shows the obtaining of daily fertilizer of guinea pigs in a sample of 1000 animals, resulting in 30 kg of manure per day. This amount of feedstock is then fed into the biodigesters, which would produce 10.5 m³/day of biogas per day with the amount of manure obtained [45,46].

Table 2. Biogas calculation.

Biogas Production Calculation		
Description	Units	Current
Nº of guinea pigs	Heads	1000
Manure produced by guinea pig	Kg/day	0.03
Total manure	Kg/day	30
Considering that 1 Kg of manure produces 0.350 m ³ of biogas		
Biogas produced per day	m ³ /day	10.5

Table 3 starts with biogas obtained per day, which is 10.5 m³/day. This material is put to work in a transformer, which gives us a value of 13.65 Kw/day, covering the daily energy demand of 13 Kw/day that the luminaires require.

Table 3. Electric energy calculation.

Electric Energy Production Calculation		
Description	unit	current
Biogas produced per day	m ³ /day	10.5
Considering that 1 m ³ of biogas generates 1.3 Kw of energy		
Electric energy generated	Kw/day	13.65

4. Discussion

The Project proposed for the River Thames consists of a group of 12 urban facilities that together form a network that relates the river as an urban element. Through these spaces, locals and tourists will be able to feel an identification with the environment and relate, giving meaning and use to them. This was generated as a support measure in front of a river that was suffering from constant pollution [47,48]. As proposed with the green corridor in Cuzco, specifically talking about the botanical garden, this urban element seeks the revitalization of the river through its urban equipment, the Terraces, which can be seen in some of the facilities of the Thames River Project, serve as an element that seeks the filtration and generation of green spaces, it is for this reason that such terraces are placed in the extension of the garden.

Likewise, the Cheonggyecheon Restoration Project arose due to the change of thought of the Chinese government, taking the citizen as a priority over the vehicle, the water body in question was being displaced by a large cart that turned the city into more concrete than vegetation. The project consisted of the replacement of these roads with a corridor that accompanies the river in its entire extension, filling it with green spaces, common areas, and urban facilities that revitalized the city and saved such an important water element [49]. The botanical garden seeks the same objective, through its elements, such as wetlands, to achieve the purification and revitalization of a river that has been forgotten by the rulers [50,51], being in its extension a landfill with an almost non-existent channel, it is worth mentioning that the project developed seeks to be a self-sustainable element, elements such as biodigesters help the production of clean energies that allow this project not to depend on elements and thus reduce the carbon footprint in a city of such value.

5. Conclusions

The project is developed as a green corridor that aims to revitalize the Huatanay River because problems such as mining and solid waste have contaminated a large part of the water body. In the extension of this urban element, the botanical garden is taken as the main agent.

This is the space that will concentrate the largest number of design strategies that will mitigate the negative impact of the river. Through biofilters, it is sought that the flora present purifies and increases the lost channel, the local flora has shown that it is an important agent when cleaning harmful substances or waste.

Likewise, the implementation of terraced systems on the edge of the river not only provides one more layer of filtration but, when adapted to social spaces, generates an interaction with the user because it seeks that the user, both local and foreign, generates an identity with an element as important as the river.

Finally, it is worth highlighting the implementation of biodigesters enhanced by guinea pigs. These have the objective of making this botanical garden a self-sustainable space because these systems provide not only daily energy but also quality fertilizers, which is an important element when talking about large spaces of vegetation. The calculations obtained showed viable results for one sector and their subsequent implementation in the remaining

sectors. The use of these species also seeks the implementation of a circular economy due to the possible consumption and distribution of their meat, which is an important source of nutrients. These design strategies were designed to mitigate the constant loss of the river and revalue it, considering also the land as an element that unites the city and improves the quality of life of the inhabitants.

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