

## Article

# Revitalizing the Canal de Castilla: A Community Approach to Sustainable Hydropower Assessed through Fuzzy Logic

Ángel Mariano Rodríguez Pérez <sup>1,\*</sup> , César A. Rodríguez <sup>2</sup> , Lucía Olmo Rodríguez <sup>1</sup>  
and Julio José Caparros Mancera <sup>2</sup> 

<sup>1</sup> Department of Engineering, University of Almería, CIMEDES Research Center (CeIA3), Ctra. Sacramento, s/n, La Cañada, 04120 Almería, Spain; lor889@inlumine.ual.es

<sup>2</sup> Department of Mining, Mechanical, Energy and Construction Engineering, University of Huelva, 21004 Huelva, Spain; cesar@didp.uhu.es (C.A.R.); julio.caparros@diesia.uhu.es (J.J.C.M.)

\* Correspondence: arp517@ual.es

**Abstract:** This study addresses the sustainable revitalization of the Canal de Castilla through a community-focused approach and an assessment via fuzzy logic of the implementation of hydroelectric turbines. The canal, built in the 18th century, played a key role in transportation and territorial unification, but the deterioration of the locks has limited its functionality. This research uses surveys as tools to assess the impact of the Canal de Castilla in different areas. With more than 85% of the inhabitants analyzed supporting measures in the areas of building and research at a high or very high level, and specifically proposing sustainable improvements that respect historical heritage, the installation of axial turbines in the cross channels is proposed as an efficient solution, highlighting their adaptability and low environmental impact. The careful selection of turbines, considering the historic nature of the canal, is supported with a detailed analysis using fuzzy logic. The innovation lies in the synergistic integration of community perceptions and technical analysis, providing a balanced foundation for decision making in heritage revitalization projects. This proactive approach seeks not only to identify challenges but also to formulate solutions, committing to sustainable development and active community participation.

**Keywords:** Canal de Castilla; axial turbines; fuzzy logic; community participation



**Citation:** Rodríguez Pérez, Á.M.; Rodríguez, C.A.; Olmo Rodríguez, L.; Caparros Mancera, J.J. Revitalizing the Canal de Castilla: A Community Approach to Sustainable Hydropower Assessed through Fuzzy Logic. *Appl. Sci.* **2024**, *14*, 1828. <https://doi.org/10.3390/app14051828>

Academic Editor: Edyta Plebankiewicz

Received: 7 February 2024

Revised: 16 February 2024

Accepted: 20 February 2024

Published: 23 February 2024



**Copyright:** © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

## 1. Introduction

The Canal de Castilla connected the Castilian plateau with the Cantabrian coast in the 18th century, enhancing transport and unifying territories. Its original purpose was to export surplus grain, although economic challenges limited its use due to the region's topography. The canal is currently a functioning hydraulic infrastructure. The management of the canal falls under the responsibility of the Confederación Hidrográfica del Duero, and it is used for irrigation and water supply [1,2]. The canal is a significant regional landmark, with importance in the economy and tourism. It also features interpretation centers, museums, and boat tours that highlight its historical legacy. This system is a historical complex with great personality, having different uses; currently it is used for water supply, and in the past it also had industrial uses. The canal has a system of locks, lockkeepers' houses, docks, bridges, warehouses, and other buildings linked to the canal. These constructions enrich the importance of the historical and cultural heritage, all of which have different degrees of regulatory protection. Within these elements, the locks particularly stand out for their key application in the Canal of Castilla due to their regulation of the water level, allowing navigability [3].

The Canal de Castilla begins in Alar del Rey. The population comprises 922 inhabitants according to the 2023 census. In its municipal area we find the first three locks. The Canal de Castilla operated through a system of locks to overcome changes in elevation of the canal bed. The lock system works with a system of gates common in this type of canal.

When a barge approaches, they open, allowing the water level to rise until it matches the next section. This method makes navigation along the channel easier [4]. Decreto 154/1991 declares the Canal de Castilla as an Asset of Cultural Interest (BIC) under the category of Historical Site, and the canal has additional areas of territorial planning [5]. The Canal de Castilla has been officially recognized as a valuable industrial asset in Spain, being an integral part of the National Industrial Heritage Plan. This recognition implies that it is granted maximum protection under the legislation on historical heritage, as established in Decreto 154/1991.

Despite the importance of the Canal de Castilla, currently, the deterioration of the locks due to lack of maintenance limits some essential activities for the activity of the canal [6]. That is why a quantitative research technique is used to assess the impact it has on the region and its inhabitants, analyzing in detail proposals for improvement. The selected quantitative research technique, of the inferential type, includes a method with surveys [7]. In this work, this technique has been chosen since it allows us to collect precise information on the perceptions, needs, and opinions of the local population through structured surveys and statistical analysis. In the context of the Canal de Castilla, where important decisions must be made about its revitalization and management, the use of quantitative techniques provides a solid basis for understanding the scope and magnitude of the canal's impact on the local community and thus guides proposals for its improvement in an informed manner. Surveys, as a research means to capture quantitative information, play a fundamental role in providing a valuable overview of various crucial aspects. This article dives into the essence of the survey, exploring its vital importance in problem identification and resolution. The careful construction of questionnaires and subsequent statistical treatment of the data reveal a precise and systematic approach to addressing specific challenges. By unraveling perceptions and needs through well-designed surveys, the door is opened to the generation of effective solutions. This process, in addition to being a key tool in decision making, highlights the ability of surveys to drive progress, offering essential perspectives that catalyze innovation and continuous improvement in diverse contexts [8,9].

Among the improvements suggested from the results of this work, the possible implementation of turbines in the canal stands out. The implementation of turbines to take advantage of the axial flow of water in canals is revealed as an advanced and efficient engineering strategy in the generation of hydroelectric energy, without requiring large-scale works [10,11]. The implementation of turbines for energy use is a sufficient condition. These turbines, meticulously designed to operate in consonance with the axial flow of water, demonstrate an exceptional capacity to adapt to the low-speed currents present in canals [12,13]. Their integration into preexisting river environments significantly minimizes environmental impact while simplifying the implementation process. The intrinsic versatility of these turbines facilitates their modular installation, allowing easy adaptation to various channel configurations without the need to make substantial modifications to the surrounding infrastructure. This approach not only enhances the generation of sustainable energy but also results in a significant reduction of costs associated with the construction of hydroelectric facilities, consolidating them as an exceedingly attractive choice for efficiently maximizing the use of axial water flow in advanced engineering environments [14].

The application of fuzzy logic in this study on the revitalization of the Canal de Castilla allows us to address the complexity inherent in decision making in a context where the variables are neither precise nor clearly defined [15–17]. Fuzzy logic is revealed as a valuable tool to model and evaluate the feasibility of integrating axial turbines in the channel, considering parameters such as water depth and flow velocity. Fuzzy logic has been highlighted not only for its success in contexts similar to the Canal de Castilla but also for its relevance in a variety of environments, including marine, river, and urban. This is due to its ability to model and evaluate uncertainty and imprecision in a wide range of situations, making it a versatile and powerful tool for decision making in engineering and environmental management. In the context of the Canal de Castilla, fuzzy logic is used to

address the complexity of turbine selection and evaluate its feasibility in a unique historical and natural environment.

The novel contribution of this work lies in the synergistic integration of community perception and fuzzy logic analysis to address the sustainable revitalization of the Canal de Castilla. While previous studies have examined the restoration of historical canals or the implementation of sustainable technologies in aquatic environments, few have so comprehensively combined local perspectives with advanced technical analysis. The application of surveys to understand the aspirations and concerns of the community, coupled with the use of fuzzy logic to assess the technical feasibility of integrating axial turbines, represents a novel approach. This holistic approach not only considers technical viability but also incorporates the voices and needs of the community, providing a more robust and balanced foundation for decision making in heritage revitalization and sustainable development projects.

In this study, the aim is to investigate the feasibility of implementing axial turbines in the Canal de Castilla after addressing key questions regarding their environmental, economic, and social impact. The initial objective of this research is to identify the issues associated with the abandonment of the Canal de Castilla [18] through the collection of perspectives and opinions of local inhabitants. With a proactive approach, this analysis seeks not only to highlight the present challenges but also to formulate solutions and proposals that optimize the use of this resource. In particular, the feasibility and benefits of energy generation through the strategic installation of turbines will be explored, with the aspiration of revitalizing and improving the management of this emblematic canal. This study stands as a commitment to sustainable development and active community participation, with the hope of transforming challenges into opportunities that benefit both the region and its inhabitants.

The contributions of this study are significant in several aspects. Firstly, it highlights the novelty of addressing the potential of hydroelectric power generation by installing turbines in a historical and protected environment such as the Canal de Castilla. This research offers an innovative approach to tackling the challenges of heritage conservation and the need for developing sustainable energy sources. Furthermore, the conclusions of this study have the potential to guide future research in this field. This work could be expanded to assess the feasibility of implementing turbines at all locks along the canal, as mentioned in the introduction, which are numerous. Such an expansion of this study would provide a more comprehensive insight into the potential of hydroelectric power generation in the Canal de Castilla and its impact on the region's energy sustainability. This study not only provides novel insights into the feasibility of using hydraulic turbines in heritage environments but also sets a starting point for future research that could further expand our understanding and application of renewable energies in historical and cultural contexts.

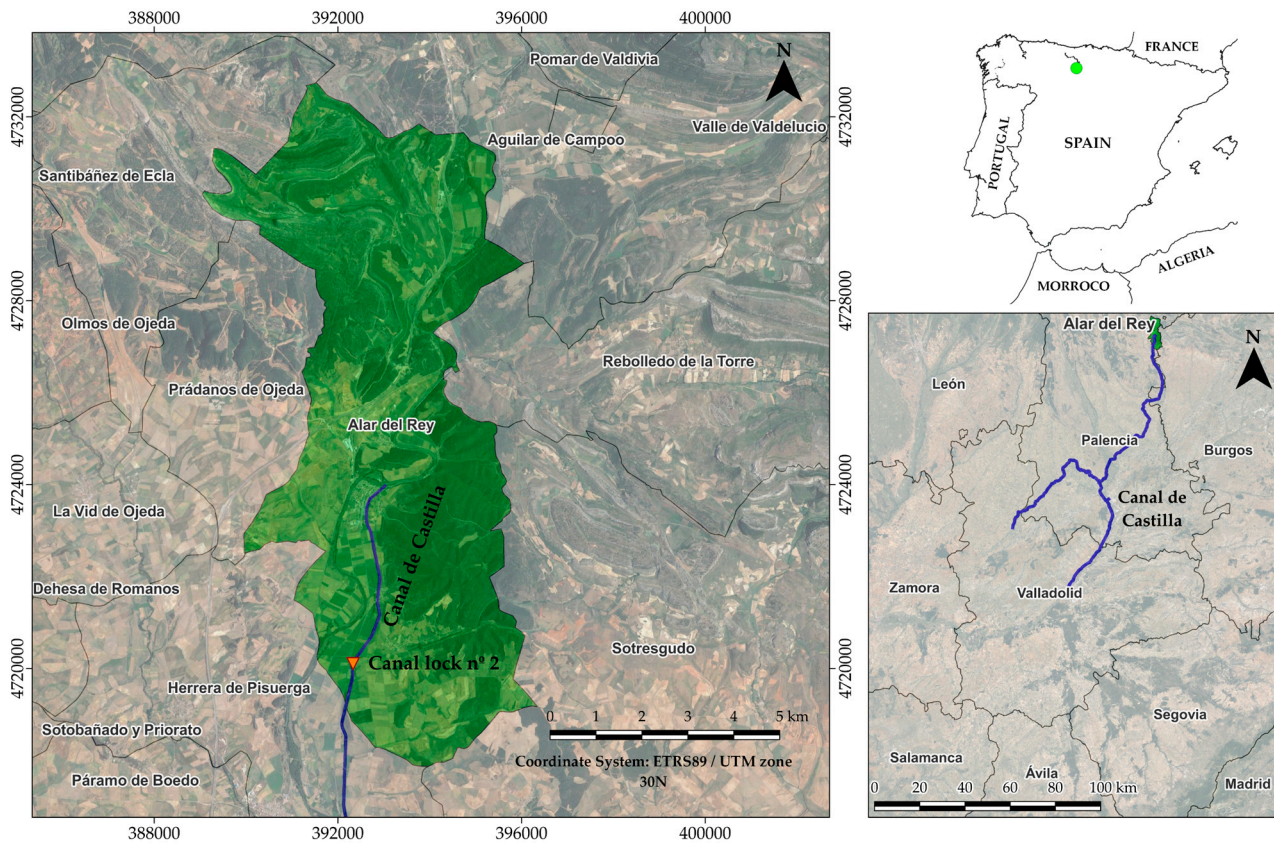
Next, this article develops in the Section 2 the population and geographic context, the location of the installation, and the selection of the turbines to be analyzed. In the Section 3, the perceived impact on the population sample in different key areas is analyzed, and from this an implementation study of the previously selected turbines is proposed, validating the proposal through the use of fuzzy logic. Finally, the Conclusions detail the main contributions of the article and its possibilities for future impact.

## 2. Materials and Methods

In the town of Alar del Rey, an exhaustive demographic study was conducted focusing on the population aged 15 and older, which comprises 829 individuals out of a total of 922 inhabitants. This study population is distributed among 406 men and 423 women. This group constitutes the fundamental sample for these surveys, which exceeded one hundred. It stands out that 68% of these surveys were carried out by women, while 32% corresponded to men. In relative terms, with respect to the study population, this represents 16% female participation and 8% male participation. Considering both genders, the total participation

is slightly above 12%. Furthermore, the average age in Alar del Rey was set at 51 years in 2022 [19].

Figure 1 presents a detailed map of the town of Alar del Rey (Palencia), highlighting the specific location of the Canal de Castilla in relation to the surrounding geography. The key points and geographical characteristics that contextualize the importance of the canal in the region are highlighted. On the other hand, it is also possible to observe the location of Lock 2 within the Canal de Castilla.



**Figure 1.** Municipality of Alar del Rey.

The selection of the lock is determined by the presence of a cross channel at Lock 2, which supplies adequate flow for the lock system. This cross channel features a draft, upstream of its spillway, between 0.5 m and 0.7 m [20,21]. In addition, an average water speed of around 1.9 m/s has been analyzed, with a typical range between 1 and 3 m/s [22,23]. Figure 2 focuses on Lock 2, serving as the specific point of interest for turbine placement. The image details the existing infrastructure at the lock, highlighting the key elements relevant to the implementation of the axial turbine. Elements such as the dimensions of the lock, water flow, and other significant aspects that support the improvement proposal are included.

Regarding turbines, the implementation of both axial turbines and traditional turbines like the Banki, designed for low-head applications, is considered. However, due to the historical and protected nature of the Canal de Castilla, only the installation of axial turbines is deemed viable, thus avoiding the need for construction works that might alter the historical structure [24]. Installation of axial turbines in transverse channels is considered the most effective solution for several reasons. First, axial turbines are known for their ability to efficiently harness water flow in canals, which makes them suitable for installation in the Canal de Castilla. Their adaptable design allows their integration into different channel configurations without the need for significant structural modifications. Additionally, these turbines have a low environmental impact, meaning that their implementation would not

cause significant damage to the surrounding ecosystem. Within the scope of our research, an exhaustive analysis of the article by Sornes et al. [25] that focuses on small-scale water current turbines designed for river applications was conducted. In this context, two specific commercial turbines that precisely meet the available speeds and depths at the selected site for implementation in the Canal de Castilla were identified. It is noteworthy that both selected turbines are exclusively for axial flow, which is crucial as this approach does not require construction works that could alter the historical structure of the Canal de Castilla, considered heritage. This meticulous selection not only ensures a technically efficient integration but also respects and adapts to the historical constraints of the environment, thereby marking a significant advance towards the sustainable revitalization of the Canal de Castilla.



**Figure 2.** Second lock in the municipality of Alar del Rey.

Table 1 details the fundamental characteristics of two selected turbines, the “Freestream Darrieus Water Turbine”, from the company Alternative Hydro Solutions Ltd. (Toronto, ON, Canada) and the “STREAM”, from the company Seabell Int. Co., Ltd. (Tokyo, Japan), which were subjected to analysis using fuzzy logic. These turbines were chosen for their distinct types and capacities, allowing exploration of their performance in various scenarios.

**Table 1.** Characteristics of the selected turbines.

WCT Device Name	Turbine Type	Min/Max Depth (m)	Min/Max Speed (m/s)	Unit Power Output
Freestream Darrieus Water Turbine	Cross-axis	Min 0.6 for high-speed stream	0.5/depends on diameter	Up to 2–3 kW
STREAM	Dual, cross-axis	0.5/no limit	0.6/no limit	Undefined

The “Freestream Darrieus Water Turbine” is noted for its cross-axis design, efficiently adapting to waters with a minimum depth of 0.6 m and high-speed water flows. Its versatility is reflected in the variability of speed, which depends on the turbine diameter and can reach up to 2–3 kW of power output. On the other hand, the “STREAM”, with

its dual and cross-axis design, shows flexibility in terms of depth and speed, although its power output capacity is not specified.

### 3. Results and Discussion

The survey sample for evaluating the Canal de Castilla's importance consists of a diverse cross section of 100 individuals from Alar del Rey, a small population of 829 according to the National Statistics Institute 2023 data. This represents a substantial proportion, suggesting a robust basis for the conclusions drawn [26].

Gender distribution skews heavily female, with women constituting 68% of respondents, potentially reflecting greater engagement or availability for surveys in this demographic. The equal split among residents indicates that the survey captures perspectives from both permanent inhabitants and those who reside in Alar del Rey seasonally or occasionally.

The educational level varies, with a significant share having completed baccalaureate or vocational training (35%), followed by those with university degrees (27%), which suggests a well-educated sample that may provide informed opinions on the canal's restoration and sustainability efforts.

Age diversity is notable, with respondents spread across life stages: 25% are in their fifties, highlighting mature insights, while the younger (18–29) and forties (40–49) cohorts represent 20% and 16%, respectively, infusing youthful perspectives and midlife practicalities into the feedback. The inclusion of seniors (8%) and the elderly (14%) adds depth, indicating intergenerational concern for the canal's future.

The results are shown in Figure 3. Displayed here is the demographic profile of respondents who participated in the survey centered around the Canal de Castilla's restoration and sustainability proposals. The pie charts meticulously detail the gender balance, residency status, educational attainment, and age range of the surveyed individuals. This visualization serves to illustrate the breadth of community engagement in this study, with particular attention to the blend of local and nonpermanent residents, the array of educational backgrounds contributing to the depth of feedback, and the wide span of ages reflecting the multigenerational investment in the canal's future. Such demographic breadth strengthens the survey's credibility, ensuring that the forthcoming results and proposed interventions for the canal reflect wide-ranging community needs and expectations.

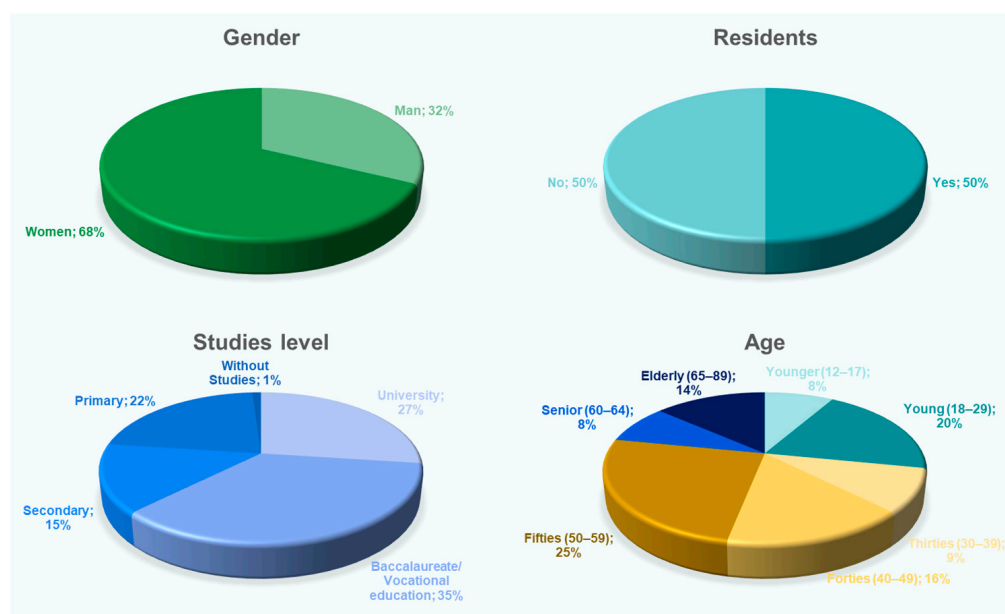
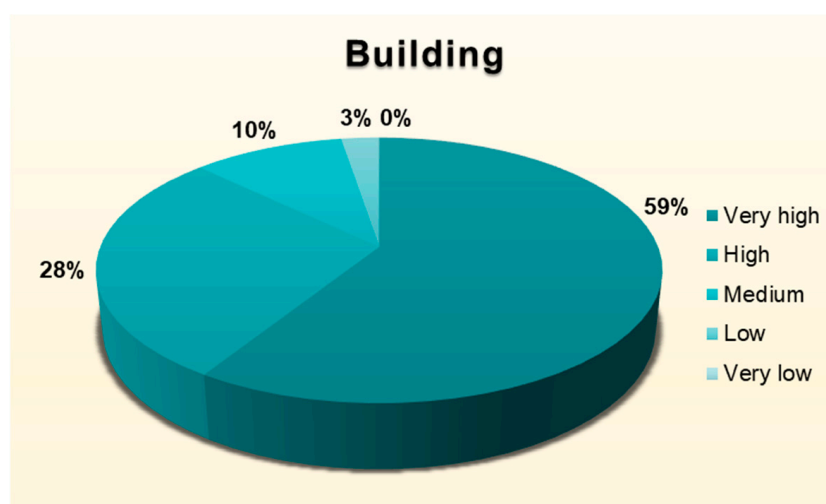


Figure 3. Demographic distribution of survey respondents for Canal de Castilla study.

The first domain surveyed was the importance, benefit, and positive impact of urban development initiatives on the Canal de Castilla, focusing on restoration and modernization efforts. Key terms used in the survey questions to elicit precise responses included “restoration impact”, “architectural integration”, “heritage conservation”, “infrastructure improvement”, and “urban revitalization”.

In analyzing the results, we find a dominant majority of 59% perceived the impact of urban development on the Canal de Castilla as “High”, while 28% considered it “Very High”. This accounts for 87% of respondents affirming significant value in building and urban development initiatives related to the canal. A smaller segment, 10%, rated the impact as “Medium”, with only 3% viewing it as “Low”. Notably, no respondents felt that the impact was “Very Low”.

These findings, visualized in Figure 4, where the darkest shades represent the most positive impact, suggest a strong community consensus on the high importance of building-related initiatives for the Canal de Castilla. The data reflect broad support for urban planning measures aimed at enhancing the canal’s structure and function, indicating a favorable public opinion towards investing in the canal’s architectural and infrastructural renewal.



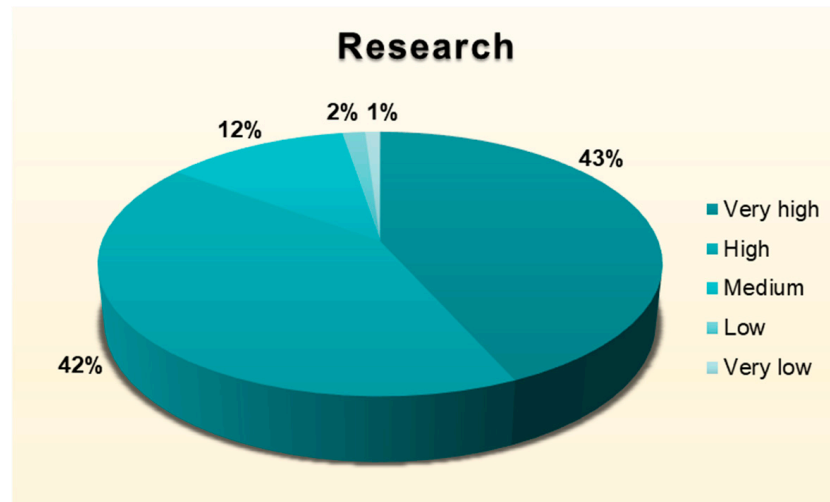
**Figure 4.** Very high perception of building and urban development impact on the Canal de Castilla.

The second area of focus in the survey was the role of research in enhancing the Canal de Castilla’s value and its future prospects. Keywords in the survey revolved around “historical research”, “sustainable engineering”, “technological innovation”, and “ecological impact studies”, aiming to quantify the perceived benefits of research on the canal’s enhancement.

Regarding the results, an overwhelming 85% of respondents rated the importance of research as “High” to “Very High”, demonstrating a clear acknowledgment of its significance. Only a small fraction, 12%, believed it holds “Medium” importance, and an even smaller 4% considered it “Low” to “Very Low”.

The gradient of blue shades in the chart in Figure 5 illustrates the weight of positive responses, with darker tones indicating a higher valuation of research. This distribution reflects the respondents’ strong support for scholarly and scientific endeavors related to the canal, suggesting that informed studies and investigations are seen as crucial for its informed restoration and sustainable development.

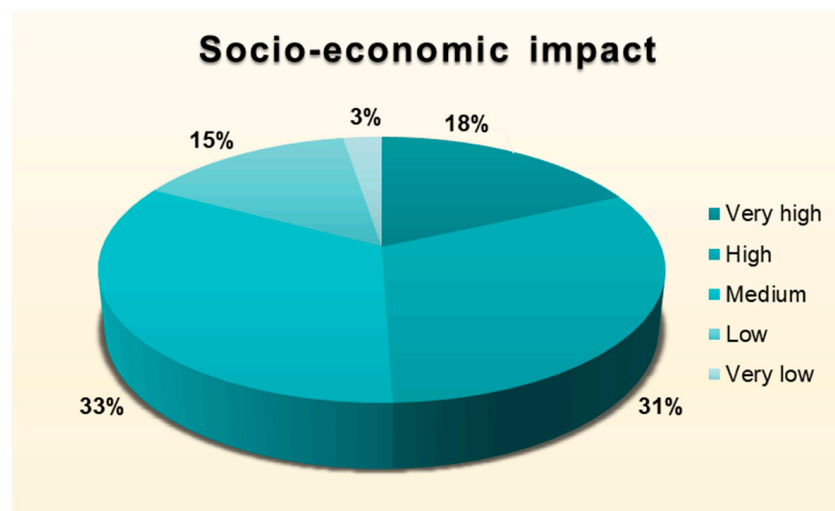
The survey’s domain of socio-economic impact addressed the perceived influence of the Canal de Castilla’s restoration on local and regional economic and social dynamics. The keywords framing the survey questions encompassed “economic revitalization”, “social benefits”, “cultural impact”, and “regional development”, facilitating precise quantification of opinions regarding the canal’s broader implications.



**Figure 5.** Very high community valuation of research impact for the Canal de Castilla.

The results show a nearly even split in perception. A marginal majority, 51%, attributed a “High” to “Very High” socio-economic impact to the canal’s restoration, reflecting optimism about its potential for stimulating growth and enhancing community well-being. Meanwhile, 49% rated the impact as “Medium” to “Very Low”, indicating skepticism or uncertainty about the expected benefits.

The chart in Figure 6, with its spectrum of colors from light to dark teal, visually captures the varied sentiments within the community. While there is a hopeful outlook from some about the canal’s potential as a catalyst for socio-economic enhancement, there is also a noticeable amount of caution or reservation from others, underscoring the need for clear communication of the restoration’s intended benefits and strategies.



**Figure 6.** High perceptions of the Canal de Castilla’s socio-economic influence.

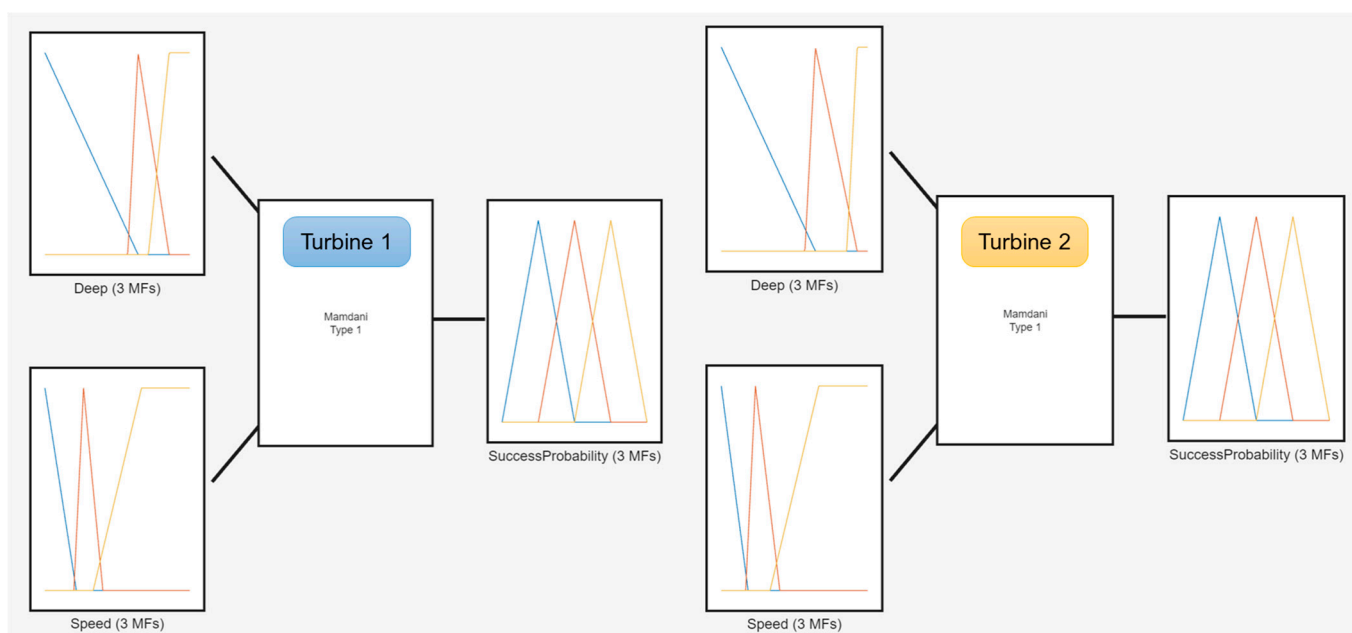
Additionally, the survey responses articulate a compelling vision for the Canal de Castilla in Alar del Rey, underlining the critical role of sustainable engineering in preserving and enhancing the canal’s heritage. The recurrent theme centers on the restoration of the canal’s locks, a task that participants agree is essential for maintaining the canal’s historical integrity and functionality. The creation of hiking and cycling routes, along with the introduction of boats for guided tours, are frequently mentioned, revealing an interest in active tourist experiences that connect visitors with local history and nature. These must be integrated together with the recovery of the canal buildings. Emphasizing the

conservation of heritage, many suggestions highlight the need for careful stewardship of the locks, ensuring any modernization efforts, such as the potential integration of turbines, align with the canal's protected status. The idea of sustainable proposals recurs, hinting at community support for eco-friendly energy solutions that could include water turbines, though these are not explicitly mentioned. The collective feedback underpins the necessity of lock restoration as part of a broader strategy to promote the canal as a hub for rural tourism and education. There is a clear advocacy for infrastructure improvements, blending the old with the new, to create an environmentally responsible attraction. This aligns with the underlying principle that technological advancements and heritage preservation should coexist, with the canal serving as a testament to historical achievement and a beacon for green innovation. The promotion of greater institutional involvement, both at the municipal and provincial levels, is suggested as key to the development and financing of these improvements. Collectively, the responses point towards an integrated strategy that values the canal's historical engineering, promotes environmental and cultural sustainability, and seeks to revitalize the local economy through conscious and enriching tourism.

Based on the survey results, the inclusion of axial turbines alongside the locks in the Canal de Castilla is both justified and encouraged. The topology of these turbines is particularly fitting as they do not require alterations to the existing structures, thereby preserving the integrity of the protected heritage site. This integration of modern technology with historic preservation serves a dual purpose: it honors the past while embracing sustainable innovation, providing a green energy source that is in line with the community's vision for environmentally responsible development.

An extensive review of the scientific and technical literature, along with an analysis of the canal's typical water conditions, was conducted to determine the operational parameters of the turbines, focusing on two critical factors: water depth and velocity. Based on these characteristics of the canal and the evaluated turbines, two similar models were selected. These models were subjected to fuzzy logic modeling to validate the typical conditions and to ascertain the optimal choice between the two axial turbines. The fuzzy logic approach was chosen for its ability to effectively manage uncertainty in the context of assessing the feasibility of turbines in the canal. In this study, we chose to use fuzzy logic given the hydraulic system in the channel; although it responds to an acceptable number of parameters to be analyzed, these can vary drastically within a limited range of values that are considered operationally acceptable. Therefore, by using this technique and applying a high resolution to the results, the global viability of the comparative installation can be analyzed in more detail, in addition to the results of multiple cases within the cases provided by the modification of variables in an unpredictable way. This methodical approach ensures that the selected turbine will align with the canal's unique features and the sustainability goals of the project, providing a data-driven solution for enhancing the canal's functionality and ecological footprint.

The fuzzy logic models for Turbine 1 and Turbine 2 are designed to evaluate the viability of installing axial turbines in the Canal de Castilla, particularly in relation to the canal's locks. These models, shown in Figure 7, utilize Mamdani-type fuzzy inference systems to process the input variables—water depth ("Deep") and flow speed ("Speed")—which are crucial factors for the successful operation of turbines. Membership functions (MFs) for "Deep" and "Speed" inputs are defined to categorize the input data into linguistic variables such as "Low", "Mid", and "High". This allows the system to handle the uncertainties and vagueness inherent in real-world applications. The output variable "SuccessProbability" is calculated based on a set of rules that relate the depth and speed to the likelihood of successful turbine operation, with its own set of MFs to quantify the probability of success.



**Figure 7.** Comparative fuzzy logic models for axial turbine selection in the Canal de Castilla.

The rule base connects the inputs to the output through logical connections, representing expert knowledge in the field. In the fuzzy logic models for Turbine 1 and Turbine 2, the rules are pivotal as they define the logic behind the decision-making process. The rule base consists of conditional statements that describe how the input variables, “Deep” (depth of the water) and “Speed” (velocity of the water flow), influence the output variable, “SuccessProbability” (the likelihood of successful turbine operation). The rules for the fuzzy logic models are designed based on the operational premise that for a turbine to function effectively in the Canal de Castilla, certain thresholds for water depth and speed must be met. The rules ensure that the turbine operates within a defined range of physical conditions that are conducive to energy generation and do not compromise the canal’s structural integrity. The rule base follows a logic structure that considers the following:

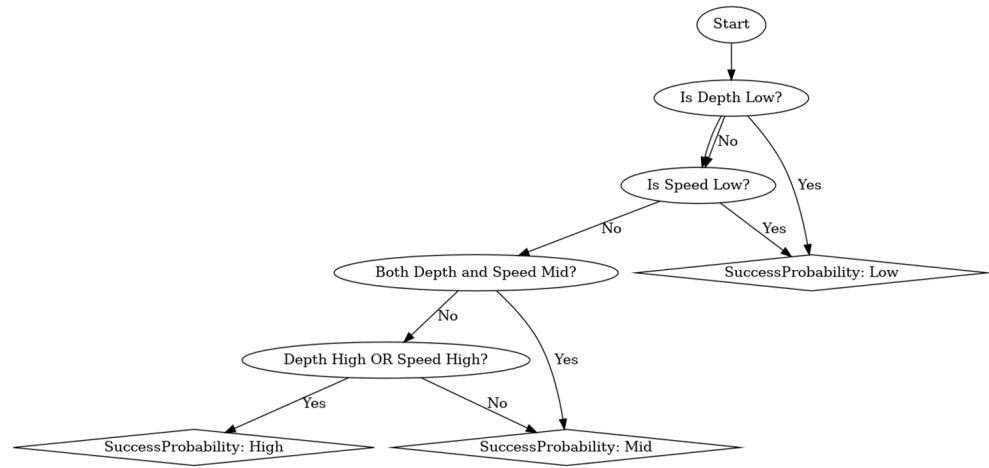
- The worst-case scenarios first, where if either of the inputs is “Low”, the success probability is also “Low”.
- A functional but limited system next, where both inputs are at least at a “Mid” level, resulting in a success probability that is moderate but not optimal.
- The best-case scenarios last, where high levels of either one or both inputs lead to a high probability of successful operation.

These rules are constructed using a combination of AND/OR operators, reflecting different possible scenarios that might be encountered in the canal’s environment. The rules are modeled to cover a comprehensive range of conditions, ensuring that the fuzzy logic system can provide a nuanced assessment of the turbine installation’s viability. The use of Mamdani-type fuzzy inference allows for a more intuitive, humanlike processing of information, enabling the system to handle the complexity and uncertainty of real-world applications in a structured manner.

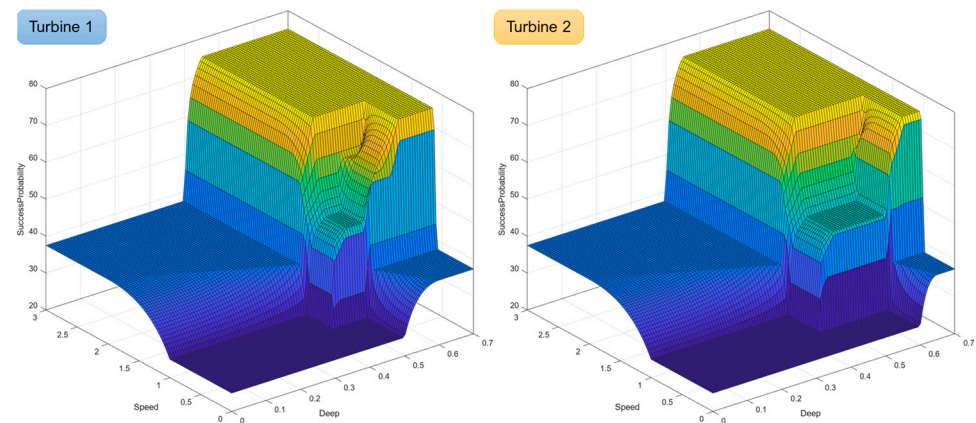
The flowchart based on which the rules processed by the fuzzy logic system are developed is presented in Figure 8.

The displayed results in Figure 9 showcase the output from the fuzzy logic models for Turbine 1 and Turbine 2. These 3D plots graphically represent the relationship between the water depth (“Deep”), flow speed (“Speed”), and resulting “SuccessProbability” for each turbine model. The objective of these models is to validate the operational range of the turbines in conjunction with the potential water conditions in the Canal de Castilla. From a global perspective, the models reveal a majority of successful outcomes within the typical

operational range, indicating that both turbines are likely to perform well under the canal’s usual conditions. However, Turbine 1 exhibits a slightly higher index of success across most cases compared to Turbine 2, though the difference in performance is relatively small. This suggests that while both turbines are viable options, Turbine 1 may offer a marginally better fit for the canal’s specific environmental and operational parameters.

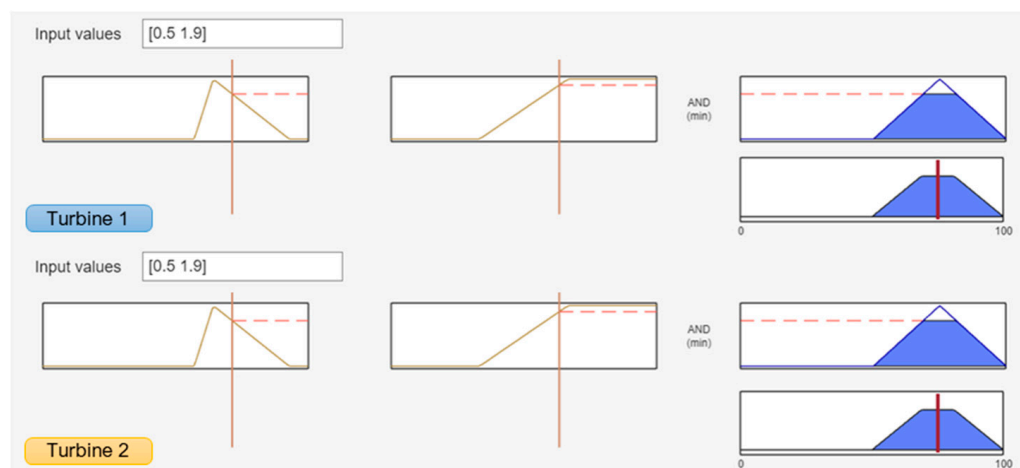


**Figure 8.** Decision flowchart for axial turbine success probability based on fuzzy logic rules.



**Figure 9.** Operational success probability of axial turbines in Canal de Castilla conditions.

Figure 10 illustrates the specific outputs of the fuzzy logic models for Turbine 1 and Turbine 2 when analyzing the conditions of 0.5 m depth and 1.9 m/s speed as base case conditions. The similarity in results for both turbines under these conditions is strikingly high, as depicted by the peak in the output membership functions on the success probability graphs. This denotes that at the given depth and speed, each turbine is predicted to operate with a high degree of success. The graphs demonstrate the fuzzy inference process, where the input values for depth and speed are processed through the membership functions and through the application of fuzzy rules, resulting in the aggregated output that predicts the success probability. The height of the peaks in the output graphs corresponds to the degree of confidence in successful operation, which in this case appears to be significant for both models. These findings suggest that with a depth of 0.5 m and speed of 1.9 m/s, both axial turbines are expected to perform well, indicating robustness in design and suitability for the canal’s analysis conditions. The graphical outputs validate the operational feasibility of both turbines, reinforcing the potential for their application in the Canal de Castilla without the need for significant structural modification.



**Figure 10.** Fuzzy logic output for axial turbine performance in designated canal conditions.

In addition to the validation of the proposed system using fuzzy logic, an estimation of the potential power generated for the base case is provided using the following hydraulic power equation:

$$P = \eta \times \rho \times A \times V^3 \quad (1)$$

where

$P$  = available hydraulic power (W).

$\eta$  = turbine efficiency (80%).

$\rho$  = water density ( $\text{kg}/\text{m}^3$ ).

$A$  = cross-section area of water flow ( $\text{m}^2$ ).

$V$  = water speed (m/s).

Then,

Width of water reaching the turbine ( $A$ ) = 0.5 m.

Depth of water reaching the turbine ( $H$ ) = 0.5 m.

Water speed ( $V$ ) = 1.9 m/s.

Turbine efficiency ( $\eta$ ) = 0.8.

Water density ( $\rho$ )  $\approx 1000 \text{ kg}/\text{m}^3$ .

Cross-section area of water flow ( $A$ ) = width  $\times$  depth of water reaching the turbine

$$A = 0.5 \text{ m} \times 0.5 \text{ m} = 0.25 \text{ m}^2.$$

$$P = 0.8 \times 1000 \text{ kg}/\text{m}^3 \times 0.25 \text{ m}^2 \times (1.9 \text{ m}/\text{s})^3 \approx 1371.8 \text{ W}.$$

Furthermore, once the proposed system has been validated using fuzzy logic, an estimation of the potential power generated for the base case is provided. Considering the diameter of the canal, water depth, and flow velocity, it is calculated that a single axial turbine could generate approximately 1.37 kilowatt-hours (kWh). However, it is important to note that this figure is a preliminary estimate and could vary depending on various factors, such as the number of turbines installed and the specific energy consumption of each lock. The substitution of energy by the turbines will largely depend on the energy demand of the lock infrastructure and the generation capacity of the turbines, which should be carefully evaluated in future feasibility studies.

#### 4. Conclusions

After the investigation carried out, it is concluded that (i) the Canal de Castilla, despite its heritage protection, shows a certain abandonment requiring economic means for its solution, (ii) there is a possibility of sustainable energy use linked to Lock 2, and (iii) after carrying out a survey in a representative sample of the population of Alar del Rey, the place where the canal begins, the degree of importance that the canal represents for the local

population is verified, exposing said sampled population to different options and solutions for the Canal de Castilla.

The comprehensive survey conducted in Alar del Rey provides valuable insights into the community's perspectives and expectations regarding restoration and sustainability initiatives for the Canal de Castilla. The diverse sample of 100 individuals, representing different age groups, educational levels, and residency statuses, establishes a solid foundation for the conclusions drawn from the survey. The results showcase broad participation that captures the views of both local and nonpermanent residents, ensuring a comprehensive understanding of the community's needs and expectations.

When examining the importance of building development initiatives for the Canal de Castilla, the survey reveals strong consensus among respondents. The majority, 87%, perceive the impact of such initiatives as "High" to "Very High". This indicates widespread support for construction-related measures aimed at improving the structure and function of the canal, emphasizing favorable public opinion towards investing in its architectural renovation and infrastructure maintenance.

Regarding the role of research in enhancing the canal's value, the survey indicates overwhelming support, with 85% of respondents rating the importance of research as "High" to "Very High". The distribution illustrates solid community backing for academic and scientific efforts related to the canal, underlining the perception of the significance of informed studies for its restoration and sustainable development.

From the survey analysis, it is evident that there is a community consensus supporting the restoration and modernization of the Canal de Castilla, particularly its locks and the introduction of sustainable technology such as axial turbines. The public's favorable perception of these developments indicates a recognition of the potential socio-economic and environmental benefits that such advancements could bring. Emphasis on heritage conservation alongside technological innovation underlines the community's desire for progress that respects and preserves historical integrity.

The fuzzy logic analysis further solidifies the feasibility of integrating axial turbines into the canal's ecosystem. Based on a previous analysis, two axial turbines were selected given that their placement in the channel would not cause modifications that alter the construction, which is protected heritage. Both turbines show high success probabilities under the examined water conditions, with the models indicating a slight preference for Turbine 1. This suggests that the canal can indeed support such sustainable technology without the need for invasive structural changes, aligning with the community-driven survey results that call for eco-friendly and culturally sensitive upgrades.

The limitations of this study primarily revolve around the constraints imposed by the Canal de Castilla being a protected heritage site and the practical considerations related to installing turbines within its watercourse. As a protected historical construction, there are strict regulations to preserve its architectural integrity and cultural significance. This imposes limitations on the extent to which modifications can be made to the canal's infrastructure, including restrictions on installing turbines directly in the watercourse, as this could hinder navigation and disrupt the historical ambiance of the canal. Therefore, while the potential benefits of implementing turbines for energy generation are acknowledged, the feasibility of such projects must be carefully evaluated within the framework of heritage conservation and practical navigation requirements.

In conclusion, the union of community insight and technical evaluation presents a compelling case for the canal's enhancement. The survey results highlight a public inclination towards sustainable development that honors the canal's legacy, while the fuzzy logic models provide a scientific foundation for selecting appropriate turbine technology. Together, they pave a well-informed path towards revitalizing the Canal de Castilla in a manner that is both technologically sound and culturally respectful.

**Author Contributions:** Conceptualization, C.A.R. and Á.M.R.P.; methodology, Á.M.R.P.; software, J.J.C.M.; validation, C.A.R. and L.O.R.; formal analysis, Á.M.R.P.; investigation, L.O.R.; resources, Á.M.R.P.; data curation, L.O.R.; writing—original draft preparation, J.J.C.M.; writing—review and editing, J.J.C.M.; visualization, C.A.R.; supervision, C.A.R.; project administration, Á.M.R.P. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Data are contained within the article.

**Acknowledgments:** CIMEDES Research Center (Ceia3) of the University of Almería.

**Conflicts of Interest:** The authors declare no conflicts of interest.

## References

- González, C.P.; Rodríguez, L.A.A. *El Canal de Castilla: Arqueología y Sociedad en el Ramal del Norte (1759–1825)*; Universidad SEK: Santiago, Chile, 2004.
- Arranz, J.B. *El Canal de Castilla*; Editorial MAXTOR: Valladolid, Spain, 2001; Volume 2.
- Geijo, J.M.; Sanchez-Lite, A.; Zulueta, P.; Sampaio, A.Z. Study of an “Artefact” of the Castilla Canal: Reconstruction of the Missing Machinery. *Machines* **2022**, *10*, 239. [[CrossRef](#)]
- Confederación Hidrográfica del Duero O.A. Plan Hidrológico de la Parte Española de la Demarcación Hidrográfica del Duero. 2021. Available online: [https://www.chduero.es/documents/20126/1418218/PHD22-27\\_140\\_00\\_Patrimonio-v00\\_00.pdf/787a9421-8198-7f35-1936-9e8f1895028b?t=1622197935438](https://www.chduero.es/documents/20126/1418218/PHD22-27_140_00_Patrimonio-v00_00.pdf/787a9421-8198-7f35-1936-9e8f1895028b?t=1622197935438) (accessed on 19 February 2024).
- Plan Nacional del Patrimonio Industrial. Available online: <https://www.cultura.gob.es/planes-nacionales/planes-nacionales/patrimonio-industrial.html> (accessed on 20 December 2023).
- Clarke, L. An overview of heritage and engineering on the canal system. *Proc. Inst. Civ. Eng. Hist. Herit.* **2015**, *168*, 93–100. [[CrossRef](#)]
- Nardi, P.M. *Doing Survey Research: A Guide to Quantitative Methods*; Routledge: Oxford, UK, 2018.
- Fowler, F.J., Jr. *Survey Research Methods*; Sage Publications: Thousand Oaks, CA, USA, 2013.
- Hämmerling, M.; Kałuża, T.; Zawadzki, P.; Zaborowski, S.; Sojka, M.; Liberacki, D.; Ptak, M. Application of Multi-Criteria Analytic Methods in the Assessment of the Technical Conditions of Small Hydraulic Structures. *Buildings* **2022**, *12*, 115. [[CrossRef](#)]
- Ismail, K.A.R.; Batalha, T.P. A comparative study on river hydrokinetic turbines blade profiles. *IJERA* **2015**, *5*, 1–10.
- Khan, M.J.; Bhuyan, G.; Iqbal, M.T.; Quaiocoe, J.E. Hydrokinetic energy conversion systems and assessment of horizontal and vertical axis turbines for river and tidal applications: A technology status review. *Appl. Energy* **2009**, *86*, 1823–1835. [[CrossRef](#)]
- Kirke, B. Hydrokinetic turbines for moderate sized rivers. *Energy Sustain. Dev.* **2020**, *58*, 182–195. [[CrossRef](#)] [[PubMed](#)]
- Eme, L.C.; Ulasi, J.A.; Alade Tunde, A.I.; Odunze, A.C. Hydrokinetic turbines for power generation in Nigerian river basins. *Water Pract. Technol.* **2019**, *14*, 71–80. [[CrossRef](#)]
- Sharif Kayyun, T.; Mohammed Hadi, H. Modeling Of Micro Hydroelectric Power Plants Utilizing Artificial Falls (Weirs) On Reach of Tigris River-Iraq. *Eng. Technol. J.* **2016**, *34*, 2106–2122. [[CrossRef](#)]
- Bogardi, I.; Bardossy, A.; Duckstein, L.; Pongracz, R. Fuzzy logic in hydrology and water resources. In *Fuzzy Logic in Geology*; Elsevier: Amsterdam, The Netherlands, 2004; pp. 153–190. VIII.
- Rodríguez-Pérez, Á.M.; Rodríguez, C.A.; Márquez-Rodríguez, A.; Mancera, J.J.C. Viability Analysis of Tidal Turbine Installation Using Fuzzy Logic: Case Study and Design Considerations. *Axioms* **2023**, *12*, 778. [[CrossRef](#)]
- Kambalimath, S.; Deka, P.C. A basic review of fuzzy logic applications in hydrology and water resources. *Appl. Water Sci.* **2020**, *10*, 191. [[CrossRef](#)]
- Elcheikh, M.; Burrow, M.P.N. Uncertainties in forecasting maintenance costs for asset management: Application to an aging canal system. *ASCE-ASME J. Risk Uncertain. Eng. Syst. Part A Civ. Eng.* **2017**, *3*, 4016014. [[CrossRef](#)]
- Demografía de Alar del Rey. Available online: <https://www.foro-ciudad.com/palencia/alar-del-rey/habitantes.html#Piramide> (accessed on 20 December 2023).
- Rigo, P.; Daniel, R. Innovative concepts in navigation lock design. In *Port Infrastructure*; TUD: Delft, Netherlands, 2010.
- Carstensen, N.; Jäppelt, U.; Willems, H. Overhaul of solid construction locks in German federal waterways. *Proc. Inst. Civ. Eng. Hist. Herit.* **2019**, *173*, 26–34. [[CrossRef](#)]
- Zhang, J.; Leontidis, V.; Dazin, A.; Tounzi, A.; Delarue, P.; Caignaert, G.; Piriou, F.; Libaux, A. Canal lock variable speed hydropower turbine design and control. *IET Renew. Power Gener.* **2018**, *12*, 1698–1707. [[CrossRef](#)]
- Niebuhr, C.M.; Van Dijk, M.; Neary, V.S.; Bhagwan, J.N. A review of hydrokinetic turbines and enhancement techniques for canal installations: Technology, applicability and potential. *Renew. Sustain. Energy Rev.* **2019**, *113*, 109240. [[CrossRef](#)]
- Adzic, F.; Stoesser, T.; Morris, E.; Runge, S. Design and performance of a novel spillway turbine. *J. Power Energy Eng.* **2020**, *8*, 14. [[CrossRef](#)]

25. Sornes, K. Small-scale water current turbines for river applications. *Zero Emiss. Resour. Organ.* **2010**, 1–19. Available online: <http://www.zero.no/publikasjoner/small-scale-water-current-turbines-for-river-applications.pdf> (accessed on 19 February 2024).
26. Instituto Nacional de Estadística. Available online: [https://www.ine.es/nomen2/inicio\\_r.do?accion=busquedaRapida&nombrePoblacion=Alar\\_del\\_Rey](https://www.ine.es/nomen2/inicio_r.do?accion=busquedaRapida&nombrePoblacion=Alar_del_Rey) (accessed on 20 December 2023).

**Disclaimer/Publisher’s Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.