Preserving Heritage Riverine Bridges: A Hydrological Approach to the Case Study of the Grau Bridge in Peru

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Abstract: Heritage bridges constitute an integral feature of the urban landscape in numerous cities. However, it is common for these structures to surpass their life cycle, rendering them ill-equipped to withstand the dynamic demands of users and extreme events, particularly hydrological occurrences. This research presents a methodology for the assessment of heritage riverine bridges, with a focus on the Grau Bridge in Peru as a case study. The investigation commences with an exhaustive literature review, complemented by a historical examination, followed by a preliminary diagnosis. Subsequently, hydrological and hydraulic studies are presented, encompassing drone surveys of the riverbed and the bridge, soil analyses, and the application of 1D and 2D models in HEC-RAS. The outcomes of this comprehensive analysis reveal the high vulnerability of the Grau Bridge. Finally, strategic interventions for its conservation are recommended.

Keywords: heritage bridges; bridges conservation; riverine bridges; 2D hydraulic models

1. Introduction

The conservation and restoration of existing infrastructure are increasingly crucial, particularly for structures possessing historical heritage value. This urgency arises from factors such as their age and the escalating threat of external elements, notably the more frequent occurrences of flooding due to climate change. A comprehensive study of this type of infrastructure should take a holistic perspective, addressing aspects ranging from urban and architectural considerations to historical, social, and economic dimensions [1].

Given the intricate nature of urban realities in Latin America [2], this study proposes an evaluation methodology from a hydrological standpoint. The objective is to contribute to the knowledge base concerning the conservation of heritage bridges situated in riverbeds. This approach is intended to better equip the entities responsible for managing such infrastructure. The proposed methodology will be validated through its application to the case study of the Grau Bridge in the city of Arequipa, Peru.

The city of Arequipa boasts several historical monuments accorded the distinction of “World Heritage of Humanity” by the United Nations Educational, Scientific and Cultural Organization (UNESCO) in 2000. These monuments predominantly comprise colonial constructions, including mansions, cathedrals, churches, and bridges [3]. Additionally, a noteworthy feature is the prevalent use of “sillar”, a volcanic material of the white ignimbrite variety, similar to ashlar, enhancing the architectural splendor of the city, often referred to as the White City.

Arequipa, the second most populated city in Peru, is home to over 1.3 million inhabitants [4] and is prone to significant earthquakes due to its location within the Pacific Ring of Fire, resting on the tectonic plates. Consequently, historical monuments in the city require continuous monitoring for seismic threats. The region experienced the impact of a powerful earthquake on 23 June 2001, in the coastal zone of southern Peru [5], revealing
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the vulnerability of structures, such as the Grau Bridge and a significant portion of the historic city center, both constructed with volcanic rock masonry walls filled with sand and lime mortar in a parallelepiped form. This earthquake showcased the fragile behavior and crack propagation along the base of these structures. Furthermore, lateral load tests have indicated that the Grau Bridge is susceptible to bending cracks in the lower zone of the central pillars during severe earthquakes (magnitude of Mw8.4) [6,7].

While seismic risks are crucial to consider, this research emphasizes hydrological risks, as bridges in Peru have demonstrated susceptibility to such phenomena as floods. It is noteworthy that flood-related incidents are a major contributor to bridge failures in river channels, causing flooding and scour in abutments and piers [8]. For instance, the El Niño Phenomenon between 2016 and 2017 resulted in the destruction of 449 bridges nationwide [9], underscoring the lack of resilience in Peru to extreme events [10]. Additionally, the design of bridges in riverbeds is often insufficient to weather the impact of climate change [11].

The Grau Bridge, along with other structures spanning the Chili River, exhibits signs of insufficient maintenance, thereby jeopardizing the safety of users [12]. Consequently, a thorough investigation into its vulnerability is imperative to mitigate associated risks, enabling necessary interventions to extend its operational lifespan while preserving its heritage significance [13,14]. Among the various risks, the flood risk is particularly critical and depends, in part, on the positioning of infrastructure such as houses along the banks of natural channels. Adjacent bridges, like the Bajo Grau Bridge located 100 m downstream from the Grau Bridge, have been closed due to non-compliance with the recommendations of the Extraordinary Maximum Water Level (E.M.W.L.) per Peruvian standards, with studies indicating their high vulnerability [15–17]. Therefore, a comprehensive evaluation of these bridges is essential to ensure optimal service levels and structural integrity [18]. Several assessment parameters for preserving heritage in river bridges are commonly employed. These encompass the historical evolution analysis of a monument through qualitative examination [19], utilization of novel historical construction materials subsequent to a monument’s collapse due to severe rainfall [20], establishment of risk matrices contingent on various return periods [21], and adoption of statistical methodologies involving observational damage probability resulting from historical events, often complemented by the utilization of digital elevation models (DEMs) [22]. This underscored uncertainty regarding peak river flow occurrences emphasizes a growing inadequacy in our preparedness due to the ramifications of climate change. This deficiency is exacerbated by the absence of quantitative investigations employing comprehensive hydrological and hydraulic evaluations, compounded further by the limited utilization of numerical models.

Recent studies propose evaluation methods for riverine bridges incorporating multi-dimensional approaches with parameters such as structural material, proximity to population centers, and the potential for flooding. While 1D hydraulic models in HEC-RAS are commonly employed in such assessments [17,18], there is a knowledge gap regarding the hydrological evaluation of heritage bridges in river channels, particularly those utilizing more representative models, such as 2D models.

This article addresses that gap through a comprehensive analysis of the Grau Bridge, incorporating a 2D hydraulic model in HEC-RAS. The methodology involves an exhaustive literature review, a historical examination of the bridge, a preliminary hydrological diagnosis, and subsequent hydrological and hydraulic studies under various scenarios. Furthermore, a multi-criteria vulnerability analysis, informed by the literature review, is presented, culminating in strategic recommendations for the conservation of the bridge. The proposed methodology is designed for adaptability and replication in studies of heritage bridges with similar characteristics.

Identifying appropriate analysis techniques is paramount to determining the life expectancy of these historical structures [23]. Currently, technologies exist that facilitate the
assessment of conservation status, particularly in heritage masonry bridges, both physically and environmentally, through structural satellite monitoring systems such as cameras, hydrometers, and echo sounders to gauge water levels, erosion, and foundation scouring [24]. Additionally, the utilization of building information modeling (BIM), finite element analysis (structural numerical analysis), and digital twins (DTs) [25,26] further enhances this evaluative process. These technologies collectively enable precise and instantaneous assessments for infrastructure management.

2. Materials and Methods

2.1. Historical Review

Until the end of the 19th century, Arequipa was clearly divided into two sectors. The central area where the main commercial activities took place and where important infrastructure such as the town hall and the hospital were located was split between the right and left banks of the Chili River [27]. Given the urban and commercial development, it was necessary to establish a communication route between the two banks, a “new bridge” in contrast to a provisional one constructed with wooden abutments and rails, but these were prone to being swept away by even the slightest increase in the flow of the Chili River [27].

In 1868, the work was started after securing the funds, materials, and a decree by the president of the republic, Pedro Diez Canseco. The “quintas”, small residences, called Vargas and Sánchez on the two sides of the Chili River were purchased, but the work was paralyzed and then totally lost due to an earthquake of approximately magnitude 9 on the Richter scale in Peru and Chile [27].

In 1881, an attempt was made to build a bridge, which was to be made of stone and iron, three meters wide and four meters high above the water level of the river, but the ravages of the War of the Pacific (1879–1883) and the occupation of the capital by Chilean troops postponed the work until 1883. That same year it was also agreed that the construction of the new bridge would be modified to 40 m long by 8 m wide, with a height corresponding to the level of the embankment that exists today, and on two abutments and two stone and ashlar pillars, similar to the structure of the Puente de Fierro (1870). On October 17, 1881, the Municipality of Arequipa agreed to the construction of a definitive bridge made of stone and ashlar and entrusted the work to the Italian architect Juan Albertazzo, for its construction during the last decades of the 19th century. However, the War of the Pacific meant the Municipality did not have the necessary funds for its construction until 1884, when the architects Juan Rodriguez and Manuel H. Prado were hired to carry out the work [27,28].

On July 14, 1884, the river was diverted from its course, which allowed construction to begin, and, in October of the same year, it was agreed to name the work “Grau Bridge”, with the old bridge as “Bolognesi Bridge” in commemoration of the heroes of the Pacific War [18]. In 1887, the first inaugurations took place despite the fact that its main function had not yet been fulfilled, and in December 1888, free transit was decreed for the recent construction; according to Juan Guillermo Carpio, the first thing to cross the bridge was a donkey [27].

Figure 1a shows the new bridge in Arequipa (Puente Grau) in 1889, one year after its construction and subsequent entry into operation according to its review and chronology (Figure 2). Figure 1b shows the Grau bridge in 1930 during the aristocratic republican transition to democracy (1895–1968).
In the 20th century, the Grau Bridge was not only one of the busiest roads but also contributed to the urban growth of the city following its entry into operation in 1888 (Figure 2). However, over time, the bridge suffered serious damage. The first incident on 21 October 1953 was when the roadway and its corresponding baluster collapsed due to excessive seepage and continuous overflows from the irrigation ditch along Cortaderas de Yanahuara Street [27], mainly due to factors such as landslides and destroyed drinking water systems that supplied the city from La Tomilla. The second incident, in early 1975, was due to an increase in the flow of the Chili River as a result of rainfall, threatening the foundations of the Bolognesi and Grau bridges due to flooding in what is now known as Barrio Obrero, eroding the pillars of the bridges [27].

It should also be added that Spanish colonialism had a clearly urban character following the founding of Arequipa on 15 August 1540 and facilitated communication between distant cities through ports, bridges, and the construction of churches [31]. As can be seen in Figure 3, four of the most important bridges in the city, both for their historical significance and their role in current transport system, are Puente Viejo or Bolognesi, Puente Bolívar or Puente de Fierro, Puente Nuevo or Puente Grau, and Puente Chilina. The Bolognesi Bridge (Figure 3a), one of the most important constructions of the colony, represented a constant concern for the local authorities, not only because of the earth-
quakes of 1582, 1600, 1604, and 1784 but also because of the torrential rains and the overflowing of the Chili River, such as the deluge of 1819, which caused flooding for five months [32]. The Fierro Bridge (Figure 3b) is now pedestrian only. Thus, in 2014, in view of the urban growth and aging of the bridges, the largest urban bridge in Peru of contemporary times was built, called Chilina Bridge (Figure 3d), whose material is prestressed concrete 562 m long with piers of 21.1 m, 28.9 m, 35 m, and 39.7 m, and seismic analysis based on an earthquake with a return period of 1000 years [33]. The Grau Bridge (Figure 3c), located in the center of the city, is 62.5 m long, 10 m wide, and 17.3 m high from the riverbed, supporting more than 10,000 vehicles per day, including light and heavy vehicles.

The Grau Bridge features a facing of ashlar blocks from the start of the arch to the top of the bridge, while from the arch springing to its foundation, it is clad in basalt blocks (Figure 4) with a lime mortar filling. Table 1 shows the general characteristics of the bridge.
Figure 4. Plans for the Grau Bridge. (a) Plan view and (b) elevation view, adapted from Guerrero and Puma (2018) [35].

Table 1. General characteristics of the bridge.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total length</td>
<td>62.5 m</td>
</tr>
<tr>
<td>Width</td>
<td>10 m</td>
</tr>
<tr>
<td>Number of arches</td>
<td>4</td>
</tr>
<tr>
<td>Arch thickness</td>
<td>1 m</td>
</tr>
<tr>
<td>Minimum span (end arches)</td>
<td>13 m</td>
</tr>
<tr>
<td>Maximum span (central arches)</td>
<td>9 m</td>
</tr>
<tr>
<td>Material composition</td>
<td>Ashlar masonry</td>
</tr>
<tr>
<td>Mortar quality</td>
<td>Low quality</td>
</tr>
<tr>
<td>Maximum height</td>
<td>17.3 m</td>
</tr>
</tbody>
</table>

2.2. Preliminary Hydrological Diagnosis

The Quilca–Chili basin (Figure 5) is located on the western slope of the Andes Mountains and therefore belongs to the Pacific Ocean slope. The basin has a complex system of dams called the “Chili Regulated System” serving to meet Arequipa’s water requirements. The Chalhuanca and Pillones dams are operated and maintained by EGASA (Empresa de Generación Eléctrica de Arequipa) and AUTODEMA (Autoridad Autónoma de Majes) of the El Frayle and Aguada Blanca dams, which protect the city of Arequipa by regulating the Chili River floods. Considering the latent risk of increasingly intense and recurrent rainfall due to the effects of climate change [36,37], a hypothetical breach of El Frayle would cause Aguada Blanca to break, generating a wave front that would reach the city. In addition, the dams’ ages and present sedimentation problems mean they do not function at the designed volumes. As a result, some 15,000 people are affected because the river flow is increased by approximately 1600 m$^3$/s [38]. Figure 5 shows the location of the Grau Bridge in the regulated system of the basin.
An example of the hydrological vulnerability faced by the city arose on 8 February 2013, when there was an exceptional rainfall of 124.5 mm in 3 h [39] and the most important creeks such as Del Pato, San Lazaro, Venezuela, and Los Incas were activated, triggering a flash flood, affecting more than 280 buildings and 53 bridges (pedestrian, vehicular, and railway), paralyzing the central areas of the city for more than a week [22]. These events aggravate the situation in the city, as they harm the population substantially on many levels [40]. In addition, it is usual for the bridges that cross the Chili River to be closed during January and February due to heavy rains, thus restricting vehicular passage [41–44]. Consequently, a hydrological evaluation of these bridges is necessary (Figure 6), including a heritage conservation perspective, the importance of which has already been highlighted.
Figure 6. Hazards due to increased flow of the Chili River caused by heavy rains. (a) Lower Grau Bridge (2011) [42]; (b) Grau Bridge (2012) [43]; (c) evaluation of the bridge due to erosion and scour; (d) base of the Grau Bridge deteriorating due to a lack of maintenance (2023) [12].

The Grau Bridge, which spans both banks of the Chili River, exhibits a lack of maintenance, posing a risk to its structural stability due to the deterioration of the masonry arches supporting the overhead structure, the asphalt layer, and similarly, the ashlar pillar that is detaching (Figure 6d). All of this stems from the absence of regular technical evaluations.

2.3. Methodology

The research methodology (Figure 7) for the preservation of the Grau Bridge heritage as a case study consisted of a comprehensive literature review. Subsequently, a diagnosis was conducted based on hydrological and hydraulic studies using representative numerical models such as one-dimensional (1D) and two-dimensional (2D) models in HEC-RAS (Hydrological Engineering Center—River Analysis System) software [45]. Consequently, the obtained results were used to establish a multi-criteria vulnerability assessment matrix based on four dimensions. Finally, strategic recommendations regarding the management of the historical monument in flood situations were generated.
The vulnerability assessment methodologies reviewed in Table 2 include evaluation parameters across environmental (E), technical (T), social (S), and economic (E) dimensions for river bridges. As these evaluation parameters are added or updated in the multidimensional matrix, the uncertainty associated with natural phenomena is reduced, better representing the vulnerability to which the infrastructure is exposed.

This study considered the vulnerability assessment matrix applied to the Grau Bridge in the city of Arequipa [18]. However, it did not take into account the historical and heritage value of the Grau Bridge. Consequently, detailed studies are required with a digital terrain model (DTM), frequency analysis of a hydrometric station, and, especially, a two-dimensional hydraulic model (2D) that better represents the hydrostatics and hydrodynamics of simulated maximum flow rates in the riverbed where the monument is located. Additionally, determining the depth of general and local scour (pillar) is crucial.

<table>
<thead>
<tr>
<th>ID</th>
<th>Author</th>
<th>Year</th>
<th>Assessment Parameters Considered in the Research</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>Martinez et al. [46]</td>
<td>2023</td>
<td>The contamination of the Chili River is due to the increase in metal concentrations (B, Cu, Fe, Mn, and Zn) from rainwater runoff that flows into the ravines and converges in the Chili River. Environmental and physical vulnerability of bridges. Temperature in relation to climate change, water quality, bridge construction materials, proximity to settlements, flood gauge, foundation protection against scour, deck erosion, flooding, and compliance with current regulations.</td>
</tr>
<tr>
<td>B3</td>
<td>Pregnolato et al. [8]</td>
<td>2022</td>
<td>Social parameters, e.g., the economy of the population, education level, and age, as well as safety facilities, shelters, and hospitals.</td>
</tr>
<tr>
<td>B4</td>
<td>Liu et al. [47]</td>
<td>2021</td>
<td>Type of housing and current data of the population in terms of economic and social risk.</td>
</tr>
<tr>
<td>B5</td>
<td>Glass et al. [48]</td>
<td>2020</td>
<td></td>
</tr>
</tbody>
</table>
3. Results

3.1. Hydrological and Hydraulic Studies

The hydrological study consisted of identifying the maximum flows in the urban area of the city of Arequipa, where the Grau Bridge is located. Hydrometric information was collected from the “Chili Regulated System”, provided by AUTODEMA with a record of 63 years (1960–2022) [54] (Figure 8).

Frequency analysis was then performed according to the Manual of Hydrology, Hydraulics and Drainage of the Ministry of Transport and Communications [MTC] [55], for eight theoretical probability distribution functions (Normal, Log Normal II/III Parameters, Gumbel, Log Gumbel, Gamma II/III Parameters, and Log Pearson type III) with seven empirical probability functions (Hazen, California, Weibull, Chegodayev, Blom, Gringorten, and Cunnane) to determine the best fit to the peak flow series through the non-parametric goodness-of-fit Kolmogorov–Smirnov test with a significance level of $\alpha = 0.05$. The empirical California function and the theoretical Pearson III function were the best fit. Figure 9 shows the frequency analysis and the fit.
A useful life (n) and an allowable failure risk (R) could then be determined for the bridge. According to the Peruvian standard [55], the R for bridges is 25% and n is 50 years. Thus, the calculation of the return period (T) of the Grau Bridge would be 174 years, but given its importance as a heritage bridge, a value of 200 years was assigned to it, to determine the Maximum Extraordinary Water Level (M.E.W.L.) and to verify a clearance gauge or height of at least 2.5 m according to the Bridge Manual [MTC] [56]. In addition, scour was calculated for a return period of T = 500 years [56]. It should be noted that, for a hydraulic study, masonry arch bridges are particularly vulnerable to scour due to the combination of their high stiffness and shallow bases [8].

Subsequently, a topographic survey was carried out with a DJI Phantom 4 RTK drone using the photogrammetry method, due to its high precision, stereoscopic vision, and differential GPS. Contour lines were obtained every meter, georeferenced from a control point provided by the Geophysical Institute of Peru (IGN) in the World Geodetic System WGS84/UTM Zone 19S.

The hydraulic simulation was carried out with the HEC–RAS [45], for periods of T = 50, T = 100, T = 200, and T = 500 years, to determine the behavior of the river, determining parameters such as water levels and velocities. Figure 10 shows the models and the bridge located at a progressive 0 + 448 km, and Table 3 shows the hydraulic parameters derived from the model, which include flows of 273 m³/s for T = 200 years and 304.3 m³/s for T = 500 years.
Figure 10. Hydraulic simulation for different return periods of the Grau Bridge with HEC–RAS software. (a) T = 50 years; (b) T = 100 years; (c) T = 200 years; (d) T = 500 years.

Table 3. Hydraulic parameters in section Km 0 + 448.0 (Grau Bridge).

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Return Period (T)</th>
<th>Probability (1/T)</th>
<th>Flow Rate (m³/s)</th>
<th>Normal Depth (m)</th>
<th>Velocity (m/s)</th>
<th>Hydraulic Area (m²)</th>
<th>Water Mirror (m)</th>
<th>Total Shear Stress (N/m²)</th>
<th>Froude Number (Fr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50</td>
<td>0.02</td>
<td>223.0</td>
<td>1.8</td>
<td>5.0</td>
<td>39.9</td>
<td>27.5</td>
<td>211.3</td>
<td>1.2</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
<td>0.01</td>
<td>248.5</td>
<td>1.9</td>
<td>5.2</td>
<td>42.9</td>
<td>28.0</td>
<td>219.1</td>
<td>1.2</td>
</tr>
<tr>
<td>3</td>
<td>200</td>
<td>0.005</td>
<td>273.0</td>
<td>2.1</td>
<td>5.3</td>
<td>45.7</td>
<td>28.4</td>
<td>225.3</td>
<td>1.2</td>
</tr>
<tr>
<td>4</td>
<td>500</td>
<td>0.002</td>
<td>304.3</td>
<td>2.2</td>
<td>5.4</td>
<td>96.1</td>
<td>29.0</td>
<td>255.8</td>
<td>1.2</td>
</tr>
</tbody>
</table>
According to the results of Table 3 for return periods of \( T = 200 \) and \( T = 500 \) years simulated one-dimensionally (1D) in HEC–RAS, they show river flow velocities greater than 3 m/s, which represents erosion problems along the channel, under a mixed regime. A supercritical flow condition (\( Fr > 1 \)) and shear stresses greater than critical in the Km 0 + 448.0 section are evidenced, which represent a dragging of particles on the bed of the channel.

The city of Arequipa is faced with extreme events such as high-intensity rains, but of short durations, which generate floods and flooding of the Chili River [57]. Over time, these extreme events (Figure 11) have triggered the activation of the Del Pato, San Lazaro, Venezuela, and Los Incas streams, as occurred in 1995, 1997, 2001, 2008, 2012, 2013, 2015, 2016, and 2020 as historical events [57–60], increasing the flow of the Chili River. Thus, as can be seen in Figure 11, produced from the frequency analysis of the Charcani station and flows resulting from rainfall in basins not gauged by historical events, flow thresholds greater than 223.0 m³/s (\( T = 50 \) years) are increasingly critical. This leaves heritage bridges exposed to the stochastic nature of floods [61].

The one-dimensional (1D) hydraulic model was generated in HEC–RAS (Figure 12), as this type of model has been shown to generate representative results regarding flood hazards in urban environments with defined and straight channels [62,63]. The hydraulic simulation considered boundary conditions, contraction (0.3) and expansion (0.5) coefficients, and Manning’s coefficients according to Cowan’s method [17]. Two hydraulic criteria were taken into account to carry out the simulation. First, for a low flow, the energy equation, quantity of motion, or momentum equation with a dredging coefficient (\( Cd = 1.33 \)) was used because of the elongated piers with semicircular ends, and the Yarnell equation because of the semicircular shape of the piers (\( K = 0.9 \)). Second, for a high flow, we used the pressure and/or weir method with a submerged inflow and outflow coefficient of 0.8.
Regarding the scour study, analyses were conducted for both general and local scour. Soil mechanics studies were undertaken to ascertain the representative diameters of the riverbed. The d50 (50th percentile diameter) was determined to be 6.5 mm. The Lischtvan-Levediev and Froehlich formula, suitable for non-cohesive soils, was employed (see Figure 13).

Figure 13. Determination of general scour (2.0 m) and local scour (4.9 m).

3.2. Multi-criteria Vulnerability Analysis

Based on the literature reviewed, a multi-criteria evaluation matrix for river bridges was applied to determine the vulnerability of the Grau Bridge [16–18]. Previously, bridges have been evaluated using this matrix, including the Grau Bridge; however, the analysis of significant parameters such as scour was not included [18] nor was a 2D model generated for a better estimation of hydraulic parameters. The matrix has 18 evaluation parameters subdivided into 4 dimensions: environmental (A1–4), technical (T1–6) social (S1–4), and economic (E1–4). The evaluation is presented in Table 4; color green indicates a low
level of vulnerability, yellow a medium level, orange a high level, and red a very high level of vulnerability.

Table 4. Grau Bridge evaluation results.

<table>
<thead>
<tr>
<th>Identification</th>
<th>Evaluation</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>The wetlands in the basin are gradually disappearing.</td>
<td>4</td>
</tr>
<tr>
<td>A2</td>
<td>The Chili River is one of the most polluted rivers in Peru due to total waste that exceeds the minimum permitted levels.</td>
<td>5</td>
</tr>
<tr>
<td>A3</td>
<td>The basin has a high exploitation of natural resources and pollution.</td>
<td>4</td>
</tr>
<tr>
<td>A4</td>
<td>Presence of small to medium-sized waste such as bottles, tires, and plastic bags.</td>
<td>3</td>
</tr>
<tr>
<td>T1</td>
<td>The Grau Bridge is built of ashlar and mortar.</td>
<td>3</td>
</tr>
<tr>
<td>T2</td>
<td>The Grau Bridge shows signs of deterioration such as cracks and fissures along the deck, pillars, and abutments.</td>
<td>4</td>
</tr>
<tr>
<td>T3</td>
<td>The Grau Bridge abutments are unprotected against extraordinary floods.</td>
<td>5</td>
</tr>
<tr>
<td>T4</td>
<td>The Grau Bridge has a clearance of 12.5 m, higher than the minimum permitted clearance of 2.5 m, according to current regulations.</td>
<td>1</td>
</tr>
<tr>
<td>T5</td>
<td>The Grau Bridge has a general scour of 2 m and a local scour of 4.9 m (total of 6.9 m), which exceed its foundation depth of 3.5 m.</td>
<td>5</td>
</tr>
<tr>
<td>T6</td>
<td>The Aguada Blanca dam is at approximately half of its total capacity due to the concentration of sediments throughout its operation.</td>
<td>3</td>
</tr>
<tr>
<td>S1</td>
<td>The areas near the Grau Bridge are commercial and agricultural, with no poverty rates.</td>
<td>1</td>
</tr>
<tr>
<td>S2</td>
<td>The population of Arequipa is poorly trained in disaster prevention and preparedness.</td>
<td>4</td>
</tr>
<tr>
<td>S3</td>
<td>The population of the city of Arequipa lives within 0.2 km of the Grau Bridge.</td>
<td>5</td>
</tr>
<tr>
<td>S4</td>
<td>The houses near the Grau Bridge are built of masonry and reinforced concrete.</td>
<td>1</td>
</tr>
<tr>
<td>E1</td>
<td>The Grau Bridge is 137 years old if dated from its inauguration in 1887.</td>
<td>5</td>
</tr>
<tr>
<td>E2</td>
<td>The Grau Bridge handles more than 10,000 vehicles per day.</td>
<td>5</td>
</tr>
<tr>
<td>E3</td>
<td>The bridge has been closed to vehicular traffic due to the increased flow of the Chili River.</td>
<td>5</td>
</tr>
<tr>
<td>E4</td>
<td>The water level has not exceeded the minimum level of the Grau Bridge deck.</td>
<td>1</td>
</tr>
</tbody>
</table>

The average score of all the evaluation parameters stood at 3.6, signifying a condition of high hydrological vulnerability. This result serves as a clear indicator that intervention is imperative for the Grau Bridge. However, the historical review emphasizes the intrinsic heritage value of the bridge, adding a layer of complexity to the decision-making process. It underscores the need to formulate conservation measures that address the hydrological vulnerability while preserving its historical significance.

In light of this dual objective, strategic recommendations are proposed to ensure that the bridge not only meets the required levels of service for users but also mitigates the risks identified through the hydrological study. This delicate balance seeks to safeguard
both the structural integrity of the bridge and its cultural heritage value, demonstrating a commitment to the preservation of historical assets while addressing contemporary challenges. The proposed recommendations aim to strike a harmonious equilibrium between functionality and heritage preservation.

3.3. Strategic Recommendations

The first strategic recommendation involves the implementation of a hydrological disaster risk management system, anchored by a comprehensive risk map of the Chili riverbed. A critical step in this process is the assessment of hazards in the vicinity of the Grau Bridge. To achieve this, a two-dimensional (2D) simulation was generated using HEC-RAS, as illustrated in Figure 14. This simulation evaluated potential risks, encompassing not only flooding but also erosion of submerged bridges, considering a return period of $T = 200$ years.

Water depths (Figure 14b), maximum velocities (Figure 14c), and the flood hazards (Figure 14d) were identified through a risk matrix. This matrix integrated hydrostatics and hydrodynamic forces to gauge the erosive potential of water during a maximum flood event. QGIS software served as the Geographic Information System tool, relying on calculations of raster pixel values [64]. This facilitated the identification of the hazard zone in the Grau Bridge location, promoting integrated risk management and enhancing resilience for formal planning versus informal growth [65,66] in the face of extreme events (Figure 14d). The strategic application of this hydrological disaster risk management system is vital for proactive planning and responses to safeguard critical infrastructure like the Grau Bridge against potential hydrological threats.

Figure 14. Flood hazard map for a return period of $T = 200$ years for the Grau Bridge and Bajo Grau Bridge: (a) digital terrain model; (b) water depths, (c) maximum velocities; (d) flood hazards.
The second recommendation advocates for the continuous 24 h monitoring of water velocities and levels during the Chili River flood season. This is to be achieved through accelerometers as an integral part of the digital twins implementation. Sensors will be strategically placed in the abutments and pillars of the Grau Bridge to furnish hydraulic and structural information related to scour and erosion in the bridge foundation. This data will prove invaluable for those responsible for managing the infrastructure. Additionally, comprehensive inspection protocols are deemed necessary for various elements of heritage and historic bridges, encompassing arches, vaults, supports, joints, pillar foundations, and abutments. These protocols will utilize valuation indexes to systematically assess and mitigate risks.

The third recommendation underscores the importance of implementing strategies for participatory community approaches. Given that heritage bridges are often situated in historic city centers and primary riverbeds that serve as water sources for consumption and economic activities, they constitute an integral part of the built environment. Therefore, it is imperative for the entire population to share in the responsibility of caring for these structures. Community approaches should extend to the establishment of early warning systems aimed at mitigating the risks associated with extreme events. This holistic involvement of the community is essential to ensure the long-term preservation and resilience of heritage bridges within the built environment.

4. Discussion and Conclusions

The urban landscapes of numerous cities worldwide, particularly in Latin America, encompass historical heritage, including bridges. As this type of infrastructure frequently approaches the end of its operational life, it struggles to meet the ever-evolving demands of users. Furthermore, the escalating severity and recurrence of extreme events amplify the vulnerability of these structures. Among the leading causes of bridge failures are those stemming from flood-related incidents, which induce scour, flooding, and other consequential effects. In light of these considerations, the authors acknowledge the significance of preserving heritage bridges situated in river channels and propose an evaluation methodology from a hydrological perspective, utilizing the Grau Bridge in Arequipa, Peru, as a case study. It should be noted that there is a certain degree of complexity in studying infrastructure in Arequipa and implementing good management practices, as there is evidence that suggests there has not been proper infrastructural governance in the past [67].

The primary outcomes of this study emphasize the bridge's importance not only from a historical standpoint but also in terms of its relevance to the city's transportation system. This characterization is meticulously detailed in the historical review of the bridge. Subsequently, a preliminary hydrological diagnosis was conducted, compiling data on the bridge's vulnerability and providing descriptions of the river and the regulated system. These initial steps were informed by an extensive review of the existing literature.

Following these preparatory stages, hydrological and hydraulic studies were undertaken. Four scenarios were proposed based on the type and significance of the structure. A drone survey of the riverbed and the bridge, as well as soil studies, were conducted. Utilizing these input parameters, 1D and 2D hydraulic models were created in HEC-RAS to determine the Extraordinary Maximum Water Level (E.M.W.L.) and assess scour in the foundation. These studies were pivotal for the multi-criteria vulnerability analysis, precisely incorporating parameters such as EMWL and scour in abutments and piers.

The vulnerability assessment revealed a high level of risk for the bridge, prompting the formulation of strategic recommendations for its conservation. These recommendations include the implementation of a hydrological disaster risk management system, leveraging emerging technologies like digital twins. This approach involves the installation of sensors on the bridge for continuous monitoring, ensuring minimum service levels and mitigating risks associated with the bridge's interaction with the flow. In conclusion, this study contributes to the enhanced management of vital infrastructure, particularly heritage bridges. Moreover, the proposed methodology is adaptable for the examination of
bridges with similar characteristics and declared as cultural heritage of the nation. This includes bridges such as Bolognesi (1608, Arequipa), Bolívar (1870, Arequipa), Colonial (1846, Puno), Pachachaca (1654, Apurímac), Calicanto (1884, Huánuco), Ambo (1879, Huánuco), Trujillo (1861, Lima), Calicanto (1861, Ancash) y Checacupe (1788, Cusco).

Bridging the gap between culture, nature, and the sound preservation of historical bridges stands as a central tenet of UNESCO’s World Heritage policies [68]. Since the adoption of the Venice Charter (1964) by the International Council on Monuments and Sites (ICOMOS) [69], measures for reconstruction have been scrutinized due to their highly sensitive nature concerning the protection of the authenticity of World Heritage sites. However, historical bridges of cultural heritage value necessitate special considerations owing to their social, cultural, and artistic significance [70]. Interventions must adhere to minimum evidence-based principles [69], prioritizing the preservation of authenticity [71,72], as these structures are increasingly threatened not only by traditional causes of deterioration but also by natural phenomena [73]. Guidelines for the conservation and restoration of historical monuments [69] encompass not only the architectural works themselves but also the urban environment in which they reside (Figure 5). Their intervention must be grounded in science and techniques [74,75] (as discussed in preliminary studies) to safeguard and manage heritage as historical and cultural monuments [76].

The guidelines and recommendations outlined in ISCARSAH documents [75] facilitate the planning of structural conservation based on qualitative data regarding the structure’s distinctive features, conception information, historical significance, material descriptions, construction techniques, deterioration processes, and damage (as discussed in the historical review section), as well as mathematical models used in modern engineering (as discussed in hydrological and hydraulic studies) to enable approaches to the conservation of cultural heritage. However, due to the lack of recognition and care, there is a need for additional efforts in this area. Consequently, it is hoped that this research will foster understanding regarding the preservation of historical bridges as world heritage.

The conditions in which heritage bridges are situated within the historic center of the city of Arequipa (Figure 3)—such as the Grau Bridge (over 130 years old), the Bolognesi Bridge (over 400 years old), and the Bolívar Bridge (over 150 years old)—it is imperative to ensure their functionality and preserve their historical heritage [77]. This requires technical evaluations and regular inspections; otherwise, the situation may lead to structural failures and even collapse due to their rigid design (masonry) when subjected to significant seismic movements and extreme hydrometeorological events such as maximum river flows during rainy seasons (January, February, and March), causing erosive actions on the Chili River (Table 3).

Furthermore, these masonry arch bridges (Figure 4) necessitate detailed studies and precise data regarding their conditions. One such technique to employ is LiDAR (light detection and ranging), along with aerial reconnaissance techniques, for their structural geometric study [78]. Similarly, heritage conservation demands interdisciplinary documentation and analysis, which are becoming increasingly complex, such as building information modeling (BIM) and 3D scanning, owing to their capabilities in capturing geometric details, construction materials, and historical elements [79,80]. However, they require significant computational power and storage space due to their high-resolution 3D models.

The advancement of hydro-environmental technologies, such as cameras, hydrological stations, hydrometers, echo sounders, sensors, and digital twins (DTs), allows for evaluations of water levels, erosion, and foundation scouring during river floods. Nevertheless, they present significant limitations in their utilization due to software interoperability issues, anomalies with detection algorithms, and macro-scale integration challenges [25].

Given these limitations and uncertainties associated with assessments of the probability of occurrence of a specific event, this study proposes as future research directions the utilization of numerical models in computational fluid dynamics (CFD). These models
solve three-dimensional motion equations (Reynolds-averaged Navier–Stokes equations) and continuity equations, using the finite volume method with turbulence models [81] implemented with Flow3D Hydro software for bridges with heritage and historical value.

Lastly, public and local participation in the protection and conservation of cultural heritage has always been a concern since the Venice Charter (1964) [82], and according to the World Heritage Convention, one of the most important objectives is “to increase the involvement of local and national populations in the protection and preservation of heritage” [83]. Thus, an integral role in the protection of historical urban landscapes is played by their inhabitants [84], and the historic center of the city of Arequipa should be no exception.

Author Contributions: Conceptualization, J.C.P.; methodology, J.C.P. and A.J.E.V.; formal analysis, J.C.P., A.J.E.V., and A.V.H.V.; investigation, J.C.P. and A.J.E.V.; data curation, J.C.P.; writing—original draft preparation, J.C.P. and A.J.E.V.; writing—review and editing, A.J.E.V. and J.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The findings of this research are supported by the data available from the corresponding author, J.C.P., upon reasonable request.

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

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