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Prioritizing Riverine Bridge Interventions: A Hydrological and Multidimensional Approach

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Abstract: Globally, most bridges fail due to hydrological causes such as scouring or flooding. Therefore, using a hydrological approach, this study proposes a methodology that contributes to prioritizing the intervention of bridges to prevent their collapse. Through an exhaustive literature review, an evaluation matrix subdivided into four dimensions was developed and a total of 18 evaluation parameters were considered, distributed as follows: four environmental, six technical, four social, and four economic. This matrix was applied to eight bridges with a history of hydrological problems in the same river and validated through semi-structured interviews with specialists. Data were collected through field visits, journalistic information, a review of the gauged basin's historical hydrological flow rates, and consultations with the population. Modeling was then conducted, which considered the influence of gullies that discharge additional flow using HEC-HMS and HEC-RAS, before being calibrated. The application of the matrix, which is an optimal tool for prioritizing bridge interventions, revealed that five bridges have a high vulnerability with scores between 3 and 3.56, and three bridges have a medium vulnerability with scores between 2.75 and 2.94. The hydrological multidimensional approach, which can be adapted for similar studies, contributes to a better decision-making process for important infrastructure interventions such as riverine bridges.

Keywords: riverine bridges; infrastructure intervention; hydrology analysis and bridges prioritization

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1. Introduction

Bridges, which usually require high investment costs to be designed and constructed, are essential for connecting populations. The most critical hazards to which they are exposed are hydrological [1–4], wherein the most recurrent failures are caused by floods that cause foundational movement [5]. Climate change directly influences hydrological events [4,6,7]. As the frequency of the maximum flood events increases, there are higher failure probabilities and an accelerated deterioration of bridges, which results in significant economic losses [4,8]. Under such a premise, it becomes a matter of priority to meet regulatory and functionality requirements [6,9], especially considering that many bridges have completed their intended life cycle. Consequently, vulnerability studies become important support tools to make decisions based on scientific evidence and thus prioritize investments in important infrastructures such as bridges [10]. However, there is a knowledge gap regarding these kinds of assessments. To reduce the knowledge gap and meet the research aim, a novel hydrological assessment methodology is proposed and implemented in a case study: the bridges of the Chili River in Arequipa, Peru.

The high amount of infrastructure affected by hydrological phenomena in Peru is alarming. For example, in the rainy season between 2022 and 2023, 118 bridges were destroyed and 188 were affected [11]. Additionally, the El Niño phenomenon that occurred between 2016 and 2017 exposed the lack of infrastructure resilience in the country [12];

493 bridges were destroyed and 943 were affected [13]. In particular, the city of Arequipa, the second most populated city in the country, was subjected to a series of hydrological impacts that suggests the necessity of a deeper evaluation to understand the effect of hydrological phenomena on bridges, with the most critical issues being (1) the progressive loss of green areas in the city [14]; (2) the lack of proper maintenance of the Aguada Blanca dam, which regulates the flow of the Chili River and is operating at almost half its capacity due to sediment accumulation [15]; and (3) the contamination of the river, which does not meet the environmental quality standard in terms of microbiological pollution [16].

The clear problems of riverine bridges caused by hydrological impacts and a lack of methodologies available to prioritize their intervention [17] suggest the need for a comprehensive proposal to evaluate bridges holistically and thus ensure optimal service levels [18,19]. In this way, the goal is to contribute to better decision making for timely interventions on the most critical bridges and to provide safety for the users. In this paper, Section 2 presents the methodology, the section under study, the literature review, the evaluation matrix, and its validation by specialists. Section 3 shows the hydrological and hydraulic analysis, as well as the evaluation and prioritization of the bridges under study. Section 4 presents the conclusions and a brief discussion.

2. Materials and Methods

2.1. Methodology

The research methodology (Figure 1) initially consisted of an exhaustive literature review on hydrological vulnerability in riverine bridges, riverbeds, and infrastructures, to obtain relevant parameters for an optimal multidimensional assessment. Such parameters were used to create a matrix project, which underwent a validation process carried out by experts through semi-structured interviews. If the matrix was not approved, the experts' recommendations were considered and a new project was prepared for validation. Once the matrix was approved, the bridges to be studied were selected and data were collected for the overall assessment, which included modeling in HEC-HMS and HEC-RAS. The matrix was applied and the results were used to prioritize the intervention on the bridges.

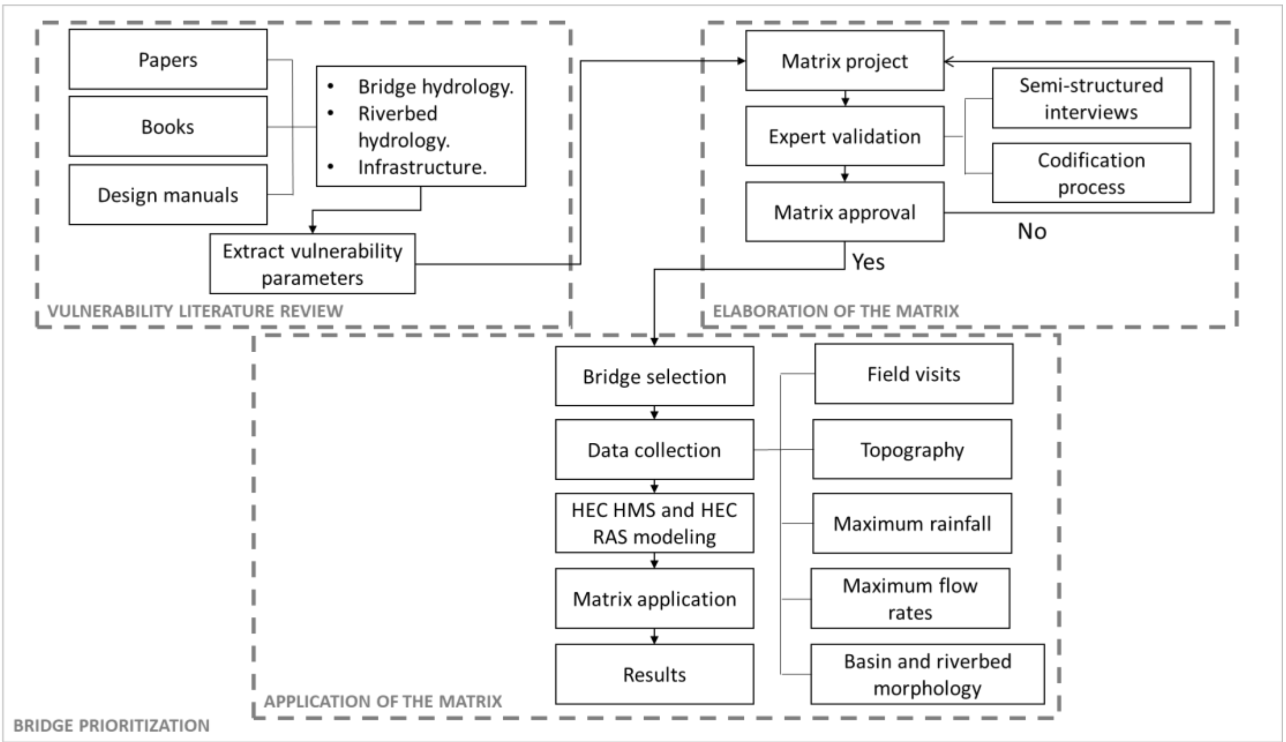

Figure 1. Research methodology.

This study proposes the use of a 1D model in HEC-RAS since it has been proven to produce reliable results [20–22] and allows for the characterization of bridges [23,24], which is important for the analysis and evaluation of common failures such as scour and erosion [25–27]. There are also other software such as FLO 2D, MIKE 11, and TELEMAC 2D [28,29], where the input parameters play an important role regardless of the program used [30]. Hence, this research thoroughly identifies such parameters.

2.2. Study Area

Eight bridges that cross the Chili River are evaluated (Table 1). If one of these bridges is closed, it would cause great economic loss, high traffic congestion, and discomfort for users, since there are few bridges that connect both sides of the city. However, there seems to be no urgency from the government to address this situation; therefore, it becomes important to develop a prioritization of the most vulnerable bridges through a comprehensive assessment that facilitates their intervention and that can be implemented in Peruvian institutions. This assessment is intended to be scalable to other groups of riverine bridges with similar characteristics to guarantee they meet the minimum demands and minimize the risk to users.

Table 1. Problems and lifespan of bridges in the Chili River.

Item	Bridge	Observation	Lifespan (Years)
P01	Grau	The bridge presents cracks and detachments in its ashlar base [31].	135 [32].
P02	Bajo Grau	Restricted to vehicular traffic due to rainfalls in 2012 and 2011 [33,34].	31 [35].
P03	Bolognesi	Bridge in operation since colonial times [33]. Heavy rainfalls weakened its structure [36].	415 [37].
P04	San Martin	Restricted to vehicular traffic due to rainfalls in 2012 and 2011 [33,34].	64 [38].
P05	De Fierro	Restricted to vehicular traffic due to rainfalls in 2019 [39]. It presents problems in one of its ashlar bases [31].	152 [40].
P06	San Isidro	The left side of the bridge is sinking [31].	57 [41].
P07	Tingo	Restricted to vehicular traffic due to rainfalls in 2020 and 2011 [34,42,43].	12 [44].
P08	Bailey	Flooding in areas surrounding the bridge, the National Water Authority reiterated its removal [45]. It was reopened to vehicular traffic [46].	07 [47].

Figure 2 shows the river section under study, which has a length of 6.95 km from bridge P01 to bridge P08. Figure 3a,b shows photographs of two of the eight bridges under study during low water levels.

While erosion, scour, and flooding are essential criteria to include in a study of bridge failures, this research presents a more in-depth study using a multidimensional approach for a more accurate assessment. Table 2 presents different approaches to assess vulnerability in bridges, as well as Peruvian standards that highlight criteria for the design of hydrologically safe bridges, which are of special interest when proposing an evaluation matrix.

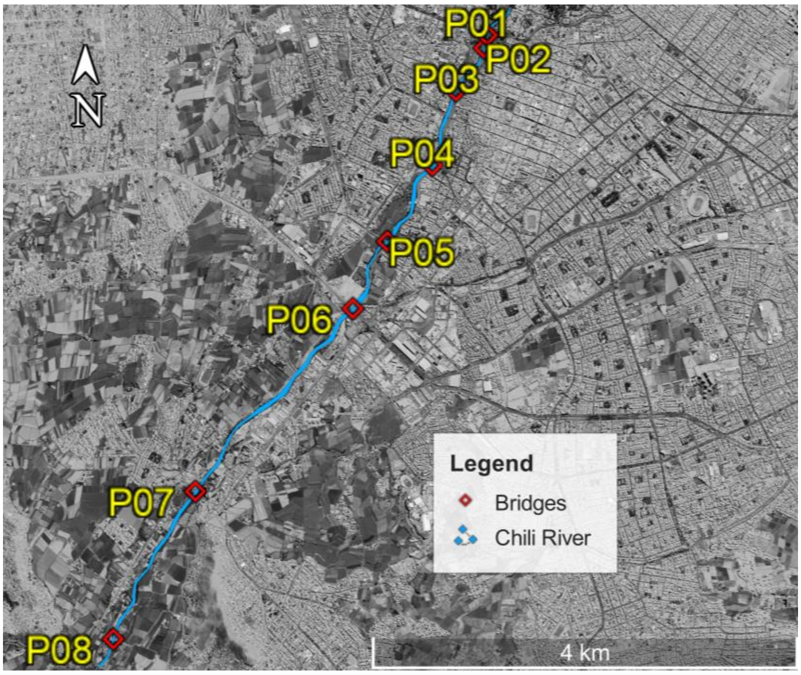

Figure 2. River section under study [48].

(**a**) (**b**)

Figure 3. Bridges under study during low water levels: (**a**) Bridge 02, Bajo Grau; (**b**) Bridge 04, San Martin. from the literature review.

Table 2. Bibliography considered for the elaboration of the evaluation matrix.

Main Precedent Studies			
ID	**Author**	**Year**	**Assessment Parameters Considered in the Research**
B1	Espinoza and Booker [17].	2023	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.
B2	Pregnolato et al. [6].	2022	Hydrodynamic thrust forces in flooding.
B3	Liu et al. [49].	2021	Social parameters, e.g., the economy of the population, education level, and age, as well as safety facilities, shelters, and hospitals.

Table 2. *Cont.*

Main Precedent Studies			
ID	**Author**	**Year**	**Assessment Parameters Considered in the Research**
B4	Glass et al. [50].	2020	Type of housing and current data of the population in terms of economic and social risk.
B5	Garrote et al. [51].	2020	Material of construction of the structure, water depth, and flood velocity.
B6	Bento et al. [18].	2020	Type and support material of the foundation, history of scour problems, type of river, and the importance of the bridge according to the traffic flowing over it.
B7	Akay and Baduna [19].	2020	Land use in the basin, surface condition, and frequency of flood recurrence.
B8	Julio Kuroiwa [52].	2019	Flow velocity and construction material from nearby houses.
B9	Geng et al. [53].	2019	Flood depth, submerged area and duration of flooding, population density, and rate of urbanization.
B10	Bhatkoti et al. [7].	2016	Climate change and the increase in impervious areas upstream.
B11	Ettinger et al. [54].	2016	Height ranges in terms of flooding, observed damage, and soil imperviousness.
B12	Bathrellos et al. [55].	2016	Slope of the study area, permeability, and vegetation cover of the soil.
B13	Mani et al. [56].	2013	Depth and duration of flooding.
Main Design Codes			
ID	**Author**	**Year**	**Assessment parameters considered in the research**
B14	Ministry of Transportation and Communications [57].	2018	Bridge clearance height, material of construction, and lifespan.
B15	Ministry of Transportation and Communications [58].	2018	Bridge clearance height.
B16	National Center for Disaster Risk Assessment, Prevention and Reduction [59].	2014	Life span, material, state of infrastructure conservation, material of housing in populated centers, and training for residents.
B17	Ministry of Transportation and Communications [60].	2008	Abutment protection, scouring, and bridge clearance height.
B18	National Institute of Civil Defense [61].	2006	Climate change, water quality, proximity to population centers, and compliance with current regulations.

The literature review suggests the need for an integration of multidimensional assessment parameters to efficiently evaluate bridges from a hydrological point of view, which, as noted in Section 1, is highly relevant if infrastructure intervention priority is to be determined.

2.3. Evaluation Matrix

After a thorough review of the body of knowledge, 18 multidimensional parameters were found to be relevant for assessing the hydrological vulnerability of riverine bridges. All parameters were studied, and it was found that they can be grouped into 4 dimensions: environmental, technical, social, and economic. The assessment matrix is shown in Table 3.

Table 3. Multidimensional vulnerability assessment matrix.

ID	Variable	Very Low: 1	Low: 2	Medium: 3	High: 4	Very High: 5
Environmental Dimension						
A1	Climate change	Temperature levels consistent over time.	Slightly above average temperature levels.	Levels are moderately above average levels.	Above average temperature levels.	Temperature levels are well above average.
A2	Water quality	No degree of contamination.	Low pollution level.	Moderate level of contamination.	High level of contamination.	Very high level of contamination.
A3	Ecological conditions	Conservation of natural resources; no deforestation nor pollution.	Low level of exploitation of natural resources and low level of pollution.	Moderate level of exploitation of natural resources and level of pollution.	High level of exploitation of natural resources and pollution.	Very high level of exploitation of natural resources, deforestation, and pollution.
A4	Waste that interrupts the flow of the river	The river is free of waste and/or garbage.	The river has a small amount of light trash, such as plastic bags and bottles.	Small to medium-sized debris such as branches, car parts, and tires are present in small quantities.	It presents medium-sized debris in regular quantities such as car parts, tires, and tree trunks.	It presents large debris in large quantities, such as tree trunks.
Technical Dimension						
ID	**Variable**	**Very low: 1**	**Low: 2**	**Medium: 3**	**High: 4**	**Very High: 5**
T1	Construction material	Reinforced concrete.	Steel.	Local materials of considerable strength.	Wood.	Adobe, cane, and less resistant materials.
T2	State of conservation	No deterioration.	Slight deterioration of structural finishes due to normal use.	There is no deterioration and, if there is, it is not compromised and is remediable, or the structural finishes and installations have visible deterioration due to misuse.	The structure shows signs of deterioration that compromise it, although there is no danger of collapse, and the structural finishes and installations have visible flaws.	The infrastructure is so deteriorated that it is likely to collapse.
T3	Flow protection in pillars and abutments	The piers and/or abutments are extremely well protected against extraordinary floods, which makes it possible to assume zero vulnerability.	The pillars and/or abutments are highly protected against extraordinary floods.	The pillars and/or abutments are moderately protected against extraordinary floods.	Pillars and/or abutments are poorly protected against extraordinary floods.	Pillars and/or abutments are unprotected against extraordinary floods.
T4	Height of the base of the board (a)	The height allows the water to flow without inconvenience. It has more than 2 m of difference between the water surface and the base of the board.	The height allows the water to flow smoothly. It has less than 2 m of difference between the water surface and the base of the board.	The height allows water to flow normally. It is less than 30 cm between the water surface and the base of the board.	The height does not allow the water to flow normally. The water level reaches the base of the board.	The height does not allow water to flow normally. Water levels exceed the level of the board.
T5	Depth of scour in shallow foundations (b)	Scour depth with a safety margin of more than 1 m.	Scour depth with a safety margin of less than 1 m.	Scour depth reaches the foundation base.	Scour depth exceeds by less than 1 m.	Scour depth exceeds more than 1 m.
T6	Current capacity of upstream dams (c)	Capacity between 81 and 100%.	Capacity between 61 and 80%.	Capacity between 41 to 60%.	Capacity between 21 and 40%.	Capacity between 0 and 20%.

Table 3. *Cont.*

Social Dimension						
ID	**Variable**	**Very low: 1**	**Low: 2**	**Medium: 3**	**High: 4**	**Very High: 5**
S1	Poverty status or human development	Nearby population without poverty.	Nearby population with the lowest percentage of poverty.	Nearby population with median poverty.	Nearby population with high poverty.	Nearby population living in total or extreme poverty.
S2	Disaster Prevention and Response (DPR) training programs for the population.	The population is constantly being trained in DPR, being updated, and participating in drills, with dissemination and total coverage.	The population is constantly trained in DPR, and its dissemination and coverage are total.	The population is regularly trained in DPR, and its dissemination and coverage are widespread.	The population is scarcely trained in DPR, and its diffusion and coverage are scarce.	The entire population does not have or develop any DPR training program.
S3	Proximity to population centers	Very far, >5 km.	Far away, 3–5 km.	Medium proximity, 1–3 km.	Nearby, 0.2–1 km.	Very near, 0–0.2 km.
S4	Material of nearby houses (d)	Masonry and reinforced concrete.	Wood and/or quincha reinforced with diagonal elements.	Quincha (cane with mud).	Adobe or Tapial.	Mat and/or cardboard.
Economic Dimension						
ID	**Variable**	**Very low: 1**	**Low: 2**	**Medium: 3**	**High: 4**	**Very High: 5**
E1	Time in operation	Less than 10 years.	Between 10 and 25 years old.	From 25 to 50 years old.	From 50 to 75 years old.	More than 75 years in operation.
E2	Importance according to the volume of vehicular traffic	Very few vehicles transiting per day.	Few vehicles transiting per day.	A regular number of vehicles transiting per day.	It is used by many vehicles per day.	It carries a high number of vehicles daily.
E3	Closure to vehicular traffic due to hydrological risk	The bridge has not been closed to vehicular traffic due to hydrological risk.	The bridge was planned to close due to hydrological risk.	The bridge has closed to vehicular traffic due to hydrological risk once.	The bridge has been closed to vehicular traffic due to hydrological risk twice.	The bridge has closed due to hydrological risk more than twice.
E4	History of flooding (e)	The bridge has never flooded.	The bridge flooded on one occasion.	The bridge flooded on two occasions.	The bridge flooded on three occasions.	The bridge flooded on four occasions.

Note: Take into account the following considerations: (a) T4: If the river is carrying logs or bulky objects, the height of 2 m will be 2.5 m; (b) T5: Not applicable if the shallow foundation depths are unknown or if the foundation piles; (c) T6: Not applicable if it is not a river gauged by a dam; (d) S4: Not applicable if the population is more than 5 km away from the bridge; (e) E4: This parameter is applied in case there is no information for parameter E3.

2.4. Matrix Validation

For the validation of the matrix, semi-structured interviews, following guidance in [62], were conducted through digital platforms with 6 bridge hydraulics specialists, informing them that the confidentiality of the interviewees would be assured and that the data collected would be used only for research purposes. The interview procedure had the following order: first, an introduction and general explanation of the research were given; second, they were shown the evaluation matrix and the bibliographic basis of each parameter; third, the questions were asked and, finally, the data were collected for the coding process. Table 4 shows the questions asked.

Table 4. Semi-structured interview questions used to validate the evaluation matrix.

ID	Questions
PR1	To what extent do you think that the criteria presented will enable a good assessment of different types of bridges with respect to their hydrological vulnerability?
PR2	What recommendations could you give to improve or optimize the matrix?
PR3	What recommendations would you give to implement the evaluation? If it is for the case of a provincial municipality and/or public entities, what process could be followed?

2.5. Codification Process

For the analysis of the answers to questions PR1 and PR2, a data coding and interpretation process (validation or recommendation) was carried out, where the 6 specialists agreed with the 18 parameters of the proposed matrix and gave some recommendations that were taken into account, such as using precise input parameters for the hydraulic model to be optimal, setting ranges for rating the vulnerability of the bridges (low, medium, and high) based on their final score in the results, and evaluating the performance of the matrix over time (Table 5). It was concluded that the criteria considered for the evaluation of bridges, from a hydrological perspective, are sufficient and represent a reliable method with which to analyze a prioritization according to vulnerability in an effective way.

Table 5. Coding of interviews on the evaluation matrix.

Answer	Important Extract	Validation (V)/Recommendation (R)
R.1.1.	"…the criteria will allow for a proper evaluation…"	V
R.1.2.	"Verify each year the performance of the matrix once implemented."	R
R.2.1.	"Optimal criteria."	V
R.2.2.	"I don't see the need for a matrix optimization."	V
R.3.1.	"…an integral analysis of the infrastructure systems is very important because this will enable prioritizing interventions"	V
R.3.2.	"…from a hydrological perspective, the matrix is very consistent."	V
R.4.1.	"It allows a global evaluation of the various aspects related to the operational level of a bridge…"	V
R.4.2.	"It is necessary to define, regardless of whether one or several bridges are analyzed, which number between 1 and 5 defines to me that the bridge is vulnerable…"	R
R.5.1.	"Precisely, to carry out all these vulnerability, hazard and risk studies, a qualitative and quantitative analysis matrix is always used, as you have indicated…"	V
R.5.2.	"…it seems to me that the most basic points are"	V
R.6.1.	"…all criteria are well developed…"	V
R.6.2.	"…as for the hydraulic modeling, the accurately determination of the roughness values is import…"	R

Regarding the answers to question PR3, the specialists recommended gradually familiarizing public entities with the methodology and clearly showing the results. In addition, it is important to note that, if the matrix is adapted to prioritize the intervention of riverine bridges with other characteristics, there should be a prior analysis so that the criteria are adapted to the study area.

3. Results

3.1. Hydrological Aspects

For the statistical analysis, 63 years of historical hydrological data (1960–2022) provided by AUTODEMA [63], the entity in charge of gauging the flows of the Chili River, were considered to obtain the maximum annual flows. Then, the probability frequency analysis was conducted using eight distribution functions, following the Peruvian guidelines [60]. The Method of Ordinary Moments enabled the estimation of the distribution parameters and, by applying the Kolmogorov–Smirnov goodness-of-fit test, the lowest theoretical delta was determined; therefore, the best distribution was selected. Two software validated the statistical analysis: Hidroesta 2.0, which uses the guidelines of the Peruvian regulations, and Hydrognomon. Both software showed the same results (Table 6).

Table 6. Theoretical delta for different types of distribution.

Distribution	Theoretical Delta
Normal	0.0937
Log Normal 2—parameter	0.1130
Log Normal 3—parameter	0.0917
Gamma 2—parameter	0.0807
Pearson III	0.0764
Log Pearson Type III	does not adjust; the scale parameter (β) is negative
Gumbel	0.0917
Log Gumbel	0.1761

The Pearson III distribution had the lowest theoretical delta with a value of 0.0764; therefore, this distribution is used to find the Chili River flows for the proposed return period (Table 7).

Table 7. Variation of the Chili River flow considering different return periods.

Chili River	
Return Period (Years)	**Flow Rate (m^3/s)**
100	247.52
140	259.32
200	271.54
500	301.90
1000	323.78

A model was developed using HEC-HMS with the data of the basins, namely, precipitation, concentration times, initial abstraction, lag time, curve number, and the impermeability of neighboring gullies [64] that increase the flow rate in the bridge section. To find the hydrographs, the streams are considered as consecutive collectors, and the flows that increase the river flow are found using the German Graphical Method, which consists of delaying the onset of the storm upstream and the time of the concentration of the current basin [65]. This procedure starts from downstream to upstream.

In the modeling of the IDF curves, the Dick Peschke formula was used [60], considering a storm duration of 3 h, which is equivalent to 180 min. For the design, the storm profile was elaborated using the Alternating Block Method for the streams studied every 10 min. For the hydrological modeling, the data obtained were entered using the SCS curve number model as the loss method and the SCS Unit Hydrograph model as the transform method. A computational interval of 1 min was set. Table 8 shows the flows obtained for return periods of 100, 200, and 500 years and their influence on each bridge.

Table 8. Modeling flow for HEC-RAS according to its return period.

Bridge	MODELING FLOW RATE (m^3/s)		
	Return Period (Years)		
	100	**200**	**500**
P 01, 02, 03, and 04	388.42	442.24	590.50
P 05 and 06	406.32	466.14	623.30
P 07 and 08	476.52	543.04	766.10

Considering a safety margin in terms of risk to the bridges, it was considered convenient to use a return period of 500 years (a useful life of 75 years and a risk of 14%) for the hydraulic modeling due to the importance of the bridges under study. Figure 4 shows the hydrographs for the 500-year return period. Likewise, the flow rates used were calibrated using videos of a maximum flood that occurred in 2012, obtaining similarity in the maximum water levels, and thus corroborating an optimal model. The modeling flow rates were then obtained: for bridges P01–P04, 590.5 m^3/s; for bridges P05 and P06, 623.3 m^3/s, and 766.1 m^3/s for bridges P07 and P08.

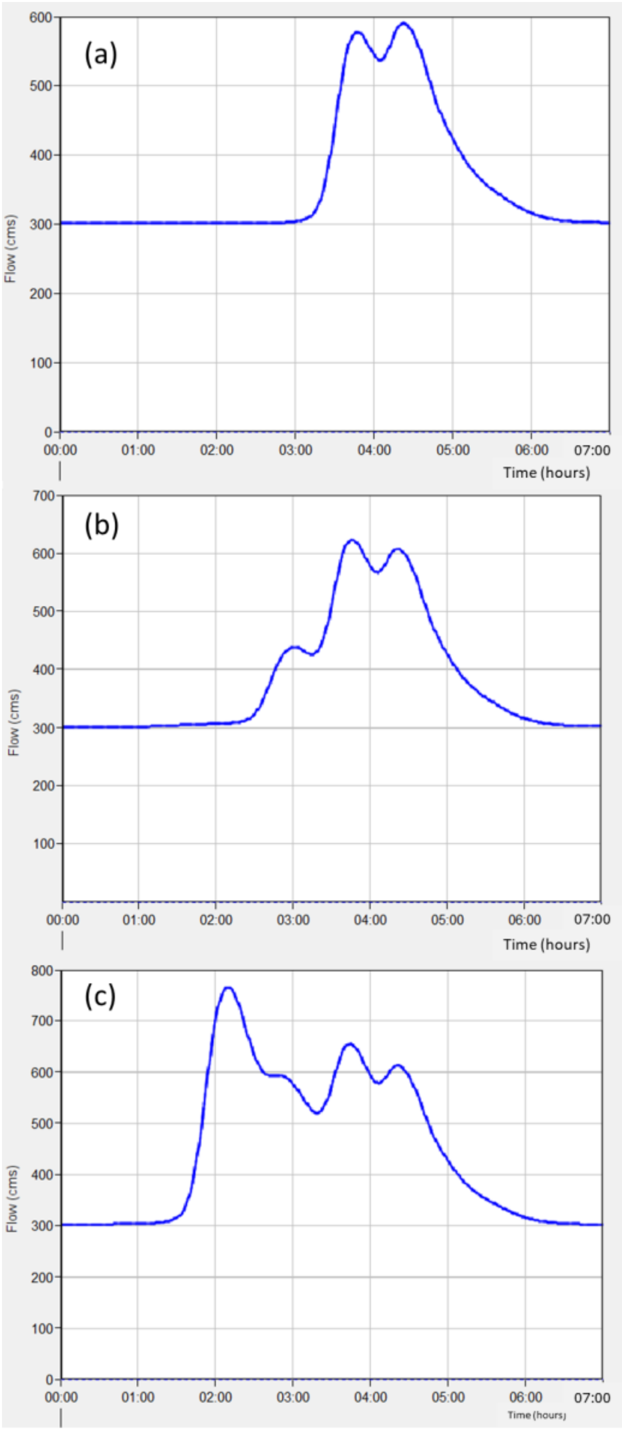

Figure 4. Shape of the resulting hydrographs of the bridges for a return period of 500 years: (**a**) Bridges 01, 02, 03, and 04; (**b**) Bridges 05 and 06; (**c**) Bridges 07 and 08.

3.2. Topographic Survey

For the topographic survey of the riverbed, information was requested from the National Water Authority, which made a topographic survey of the marginal strip of the Chili River in 2015 [66]. However, since the surrounding floodable area was not contrasted, the riverbed survey was superimposed on an ALOS PALSAR satellite image DEM of 12.5 m [67], thus having an adequate topography for hydraulic modeling. CIVIL 3D software was used to generate the raster, where the topographic surface was exported to a TIFF file to be used in HEC-RAS. Field visits were made to obtain roughness coefficients using Cowan's method [68]; the coefficients were verified and compared with previous investigations in the same river reach [69], thus validating a correct determination.

3.3. Hydraulic Modeling

A 3D view from the HEC-RAS of Bridges P01, P02, P03 (Figure 5), P04, P06, P07, and P08 (Figure 6) is shown. Bridge P05 was not modeled because it is not floodable due to its high height. Figure 7 shows the transversal sections of Bridges P02 and P07. The results of the Extraordinary Maximum Water Levels (EMWLs) were used in the analysis of the vulnerability of the bridges using the proposed assessment matrix, specifically in parameter T4.

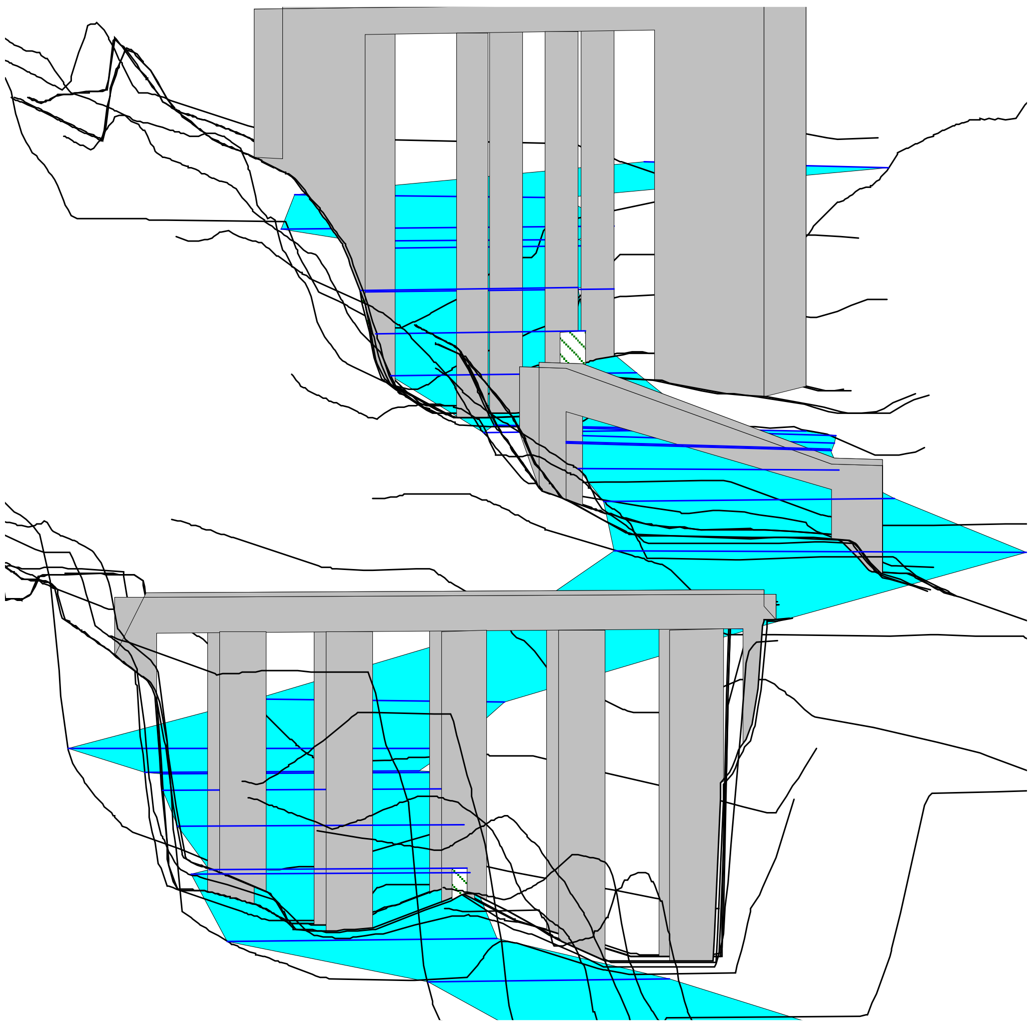

Figure 5. Three-dimensional hydraulic modeling view of Bridges 01, 02, and 03 (upstream to downstream).

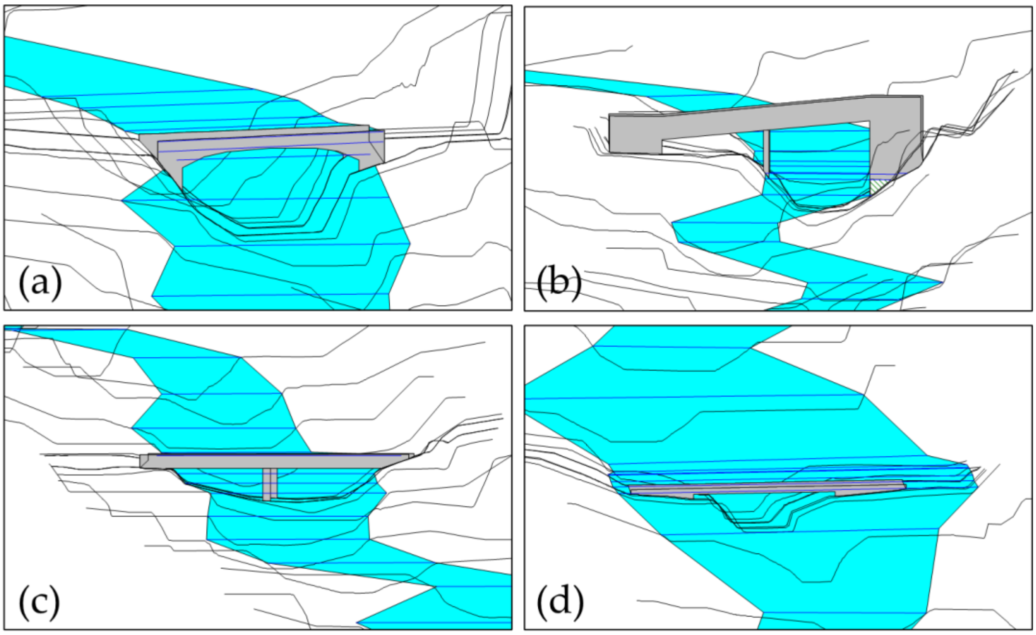

Figure 6. Three-dimensional views of bridge hydraulic modeling: (**a**) Bridge 04, (**b**) Bridge 06, (**c**) Bridge 07, and (**d**) Bridge 08.

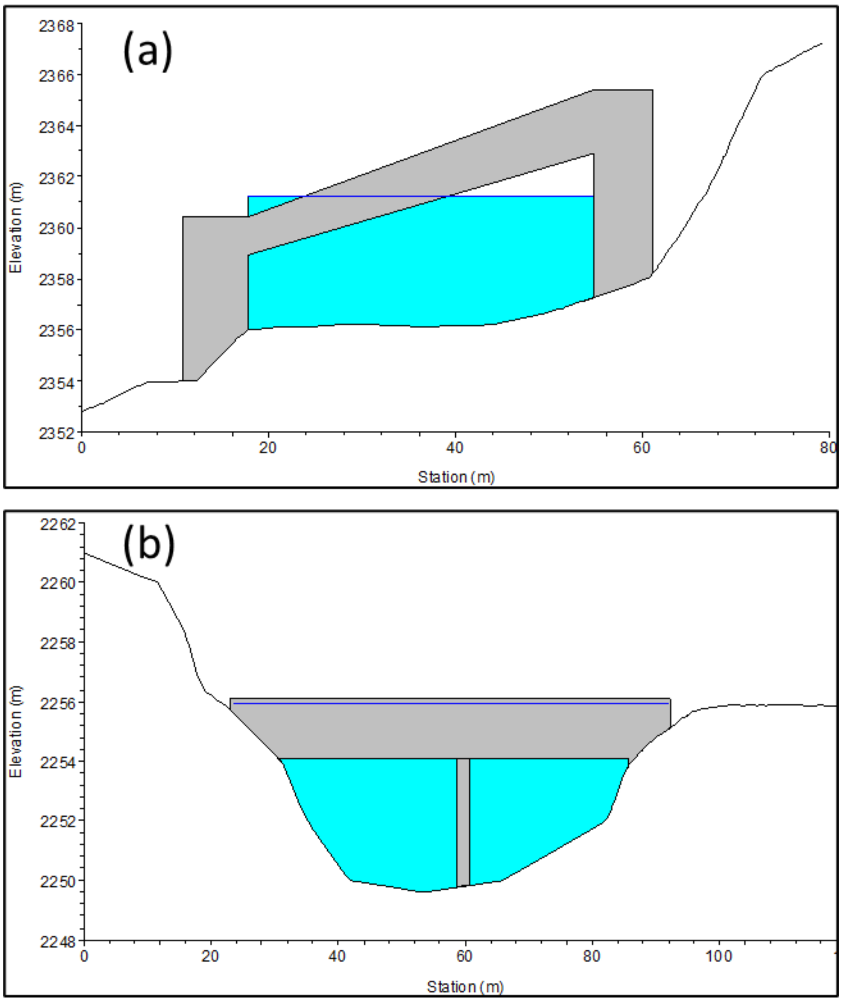

Figure 7. Transversal sections of Bridges (**a**) P02 and (**b**) P07.

3.4. Bridge Assessment

Table 9 evaluates the parameters that all the bridges under study have in common and shows their scores. Table 10 shows the evaluation of the remaining parameters of the matrix of Bridge P04 as a typical analysis, being applied in the same way to the other bridges.

Table 9. Evaluation of common parameters in the bridges under study.

ID	Evaluation	Score
A1	Increased temperature due to climate change, which is exacerbated by the progressive loss of the countryside and green areas in the city.	4
A2	The section under study presents contamination in terms of microbiological parameters, where they exceed the environmental quality standard.	4
T9	The Aguada Blanca dam has reached its useful life expectancy and, due to a lack of maintenance and sediment cleaning, its storage capacity has been reduced to 50%.	3

Table 10. Typical evaluation: Bridge P04—San Martin.

ID	Evaluation	Score
A3	It has a moderate level of contamination and exploitation of natural resources.	3
A4	There is a large amount of algae and grass, as well as logs, tires, and plastic bags.	4
T1	The bridge is made of reinforced concrete material.	1
T2	The bridge shows signs of deterioration that compromise it, although there is no danger of collapse, and the finishes and installations have visible flaws. There are also cracks on the right side of the bridge, and the bridge's steel is unprotected in some areas.	4
T3	The bridge abutments are unprotected against extraordinary floods.	5
T4	The water flow is close to impacting a maximum flood that occurred in 2011 and the hydraulic modeling shows that it impacts the deck and overflows.	5
S1	There are houses made of masonry material near the bridge, and the surrounding area is a business housing and farming area, with no poverty indexes.	1
S2	Stores and/or businesses that live near the bridge were consulted and indicated that the municipality does not provide them with training on disaster prevention and responses to hydrological events. They mentioned that, eventually, the municipality cleaned the riverbed.	4
S3	It was observed that the population lives less than 0.2 km away.	5
S4	The houses are made of brick masonry.	1
E1	The bridge was inaugurated on 11 August 1959, and has been in operation for more than 63 years.	4
E2	It is a bridge over which many vehicles travel, generates high economic income, and is considered very important by the population.	5
E3	The bridge was closed to vehicular traffic twice due to hydrological events.	4

The matrix was applied in the same way to the remaining bridges, obtaining the results shown in Table 11. It is worth mentioning that the depths of the foundations of the bridges are not available to verify the T5 parameter. Likewise, as mentioned in the matrix, the E4 parameter is only used if the E3 data are not available.

Table 11. Vulnerability assessment score of the study bridges.

ID	P01	P02	P03	P04	P05	P06	P07	P08
A1	4	4	4	4	4	4	4	4
A2	4	4	4	4	4	4	4	4
A3	3	3	3	3	2	3	3	3
A4	3	3	3	4	1	2	2	2
T1	3	1	3	1	2	1	1	2
T2	3	3	3	4	4	2	2	1
T3	5	3	2	5	2	3	4	3
T4	1	5	1	5	1	1	4	5
T5	-	-	-	-	-	-	-	-
T6	3	3	3	3	3	3	3	3
S1	1	1	1	1	1	1	2	1
S2	4	4	4	4	4	4	4	5
S3	5	5	5	5	5	5	5	5
S4	1	1	1	1	1	1	1	1
E1	5	3	5	4	5	4	2	1
E2	5	5	5	5	4	5	5	4
E3	1	4	1	4	3	1	4	3
E4	-	-	-	-	-	-	-	-
Average	3.19	3.25	3.00	3.56	2.88	2.75	3.13	2.94

Peruvian regulations suggest using four levels of vulnerabilities when analyzing risks (low, medium, high, and very high). The final score considers values below 50% to indicate medium and low levels of vulnerability [61]. However, as this methodology is designed to prioritize the intervention of bridges, and being half of the maximum vulnerability assessment value, three levels of vulnerability are considered. Bridges with a final average score <2.5 have a low vulnerability and no intervention is required. Bridges with values <3 and $\geq$2.5 have medium vulnerability and need an intermediate prioritization; bridges with values $\geq$3 have high vulnerability and urgent intervention is required. A summary of the eight bridges is presented in Table 12.

Table 12. Summary of final bridge scoring and prioritization.

Priority	ID	Bridge	Score	Vulnerability
1	P04	San Martín	3.56	High
2	P02	Bajo Grau	3.25	High
3	P01	Grau	3.19	High
4	P07	Tingo	3.13	High
5	P03	Bolognesi	3.00	High
6	P08	Bailey	2.94	Medium
7	P05	De Fierro	2.88	Medium
8	P06	San Isidro	2.75	Medium

Applying the multidimensional hydrological vulnerability assessment matrix to the Chili riverbed, the San Martin, Bajo Grau, Grau, Tingo, and Bolognesi bridges show high vulnerability, with scores of 3.56, 3.25, 3.19, 3.13, and 3, respectively. In addition, the Bailey, De Fierro, and San Isidro bridges have medium vulnerability, with scores of 2.94, 2.88, and 2.75, respectively.

4. Conclusions

Based on an exhaustive review of the available literature, a hydrological vulnerability assessment matrix was developed and subdivided into four dimensions: environmental, technical, social, and economic. A total of 18 evaluation parameters were considered and distributed as follows: four environmental, six technical, four social, and four economic parameters. Each parameter has five evaluation levels: very low, low, medium, high, and very high, with values between 1 and 5, respectively. To determine the final weighting, the scores of the parameter evaluations were averaged. Bridges with an average ≥3 were considered high vulnerability bridges, between <3 and ≥2.5 were considered medium vulnerabilities, and <2.5 was considered low vulnerability. The matrix was validated by six experts in the field of bridge hydraulics through semi-structured interviews and a data-coding process. In addition, the matrix was validated by applying it to eight bridges from the Chili River, demonstrating its effectiveness. Therefore, it is concluded that the matrix allows an optimal vulnerability assessment of bridges from a hydrological perspective. The matrix and the methodology can be adapted for other riverine bridge evaluations. Moreover, further work could evaluate the correlation between the types of bridges, their particular hydrological environment, and their vulnerability.

The vulnerability of the bridges was determined through hydrological analysis and hydraulic modeling. Regarding the hydrological study, the most relevant input parameter was the series of maximum annual flows, since the riverbed is gauged; from this, historical data of 63 years were obtained. Through hydrological statistics, critical scenarios were determined according to the normative recommendations for flow estimation. Additional flows were considered due to the gullies annexed to the river. HEC-HMS software and analysis were used to estimate the modeling flow rates and a flow rate of 590.5 m^3/s was obtained for Bridges 01, 02, 03, and 04; 623.3 m^3/s for Bridges 05 and 06, and, for Bridges 07 and 08, a flow rate of 766.1 m^3/s. These flows were validated through recordings of the interaction of the bridges with a maximum flood that occurred in 2012. Regarding the hydraulic modeling, the HEC-RAS software was used to determine the EMWL of each bridge, revealing that Bridges 02, 04, 07, and 08 are impacted by the flow.

After applying the evaluation matrix, the bridges under study were prioritized for intervention in the following order: San Martin, Bajo Grau, Grau, Tingo, Bolognesi, Bailey, De Fierro, and San Isidro, with a vulnerability score of 3.56, 3.25, 3.19, 3.13, 3, 2.94, 2.88, and 2.75 respectively. This research contributes to the actors in charge of managing bridges throughout their life cycle, such as local and regional municipalities, with an optimal tool for prioritizing bridge interventions, to ensure that they meet minimum service levels and do not jeopardize the safety of their users.

Many bridges around the world have reached the end of their life cycle and are vulnerable to meteorological events. Investing in bridge intervention is therefore a necessity. However, many countries, particularly developing ones such as Peru, find it difficult to prioritize their investments. Many factors can be attributed to this difficulty, for example, the financial resources available and knowledge of infrastructure are important to intervene. While it is true that this study contributes to better decision-making for bridge interventions from a hydrological perspective, it is necessary to complement the analysis by including aspects such as structural ones, i.e., considering the various loads to which bridges are subjected, such as car and wind loads. Moreover, there are different types of interventions, which will also depend on the actors in charge of managing the bridges. The options range from complete reconstruction to constant monitoring to provide safety for users. For example, digital twins could be implemented for real-time monitoring. Regardless of the decision taken, this study, through a multidimensional analysis, emphasizes the urgency surrounding the state of the bridges and the risk they represent for their users, so that, effectively, their intervention is prioritized.

Concerning the evaluation, there are additional parameters that could be integrated into the assessment matrix, such as maintenance to the riverbed and bridge, type of river, type of foundation of the bridge, and type of soil where it is found. Regarding hydraulic modeling, other types of 2D and 3D modeling can be implemented. In addition, it is important to properly validate the modeling flow because it is directly related to the return period, and the regulations require a period which, in many cases, undersizes the clearance height of the bridge, making it more vulnerable to extreme events. Moreover, if the evaluation matrix is replicated, regulations from other countries should be taken into account since some of the Peruvian guidelines are outdated, and improvements should be implemented.

As noted, further work can complement this research at many levels. For instance, the inclusion of other hydrological and non-hydrological parameters, analyzing the variations of other hydraulic models, studying the methodology implementation efficiency in local governments, and the type of intervention that could be applied to the most vulnerable bridges, which could include cost–benefit analyses, so that interventions are effectively applied to a series of bridges, assessing their impact on infrastructure and society.

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