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Prioritizing Riverine Bridges Interventions: A Hydrological Multidimensional Approach

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Abstract: Globally, bridges fail mostly due to hydrological causes such as scour or flooding. Therefore, under a hydrological approach, this study proposes a methodology that contributes to prioritize the intervention of bridges to prevent their collapse. Through an exhaustive literature review, an evaluation matrix subdivided into 4 dimensions was developed and a total of 18 evaluation parameters were considered, distributed as follows: 4 environmental, 6 technical, 4 social and 4 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, review of the gauged basin historical hydrological flow rates and consultations with the population. Then, the modeling, which considered the influence of gullies that discharge additional flow, was carried out using HEC-HMS and HEC-RAS and subsequently calibrated. The application of the matrix revealed that five bridges have a high vulnerability, and three bridges have a medium vulnerability. The multidimensional approach can be adapted for studies of other riverine bridges.

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

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], where the most recurrent failures are caused by floods that cause foundation movement [5]. Climate change directly influences hydrological events [4,6,7]. As the frequency of maximum flood events increases, there are higher failure probabilities and 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]. To meet this objective, a comprehensive 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, the El Niño phenomenon that occurred between 2016 and 2017 exposed the lack of infrastructure resilience in the country [11]; 493 bridges destroyed and 943 affected [12]. 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, the most critical issues being: 1) the progressive loss of the green areas in the city [13]; 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 [14]; and 3) the contamination of the river that does not meet the environmental quality standard in terms of microbiological pollution [15].

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The clear problems of riverine bridges due to hydrological causes and the lack of methodologies to prioritize their intervention [16], suggests a comprehensive proposal to evaluate them holistically and thus ensure optimal service levels [17,18]. In this way, it is intended to contribute to better decision making for timely intervention of the most critical bridges and to provide safety to those who 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, 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 consists of an exhaustive literature review on hydrological vulnerability in riverine bridges, riverbed, and infrastructures, to obtain relevant parameters for an optimal multidimensional assessment. Such parameters are used to elaborate a matrix project, which is submitted to a validation process by experts through semi-structured interviews. Once the matrix is approved, the bridges to be studied are selected, data are collected for the overall assessment, which includes modeling in HEC HMS and HEC RAS. The matrix is applied, and the results are used to prioritize the intervention on the bridges.

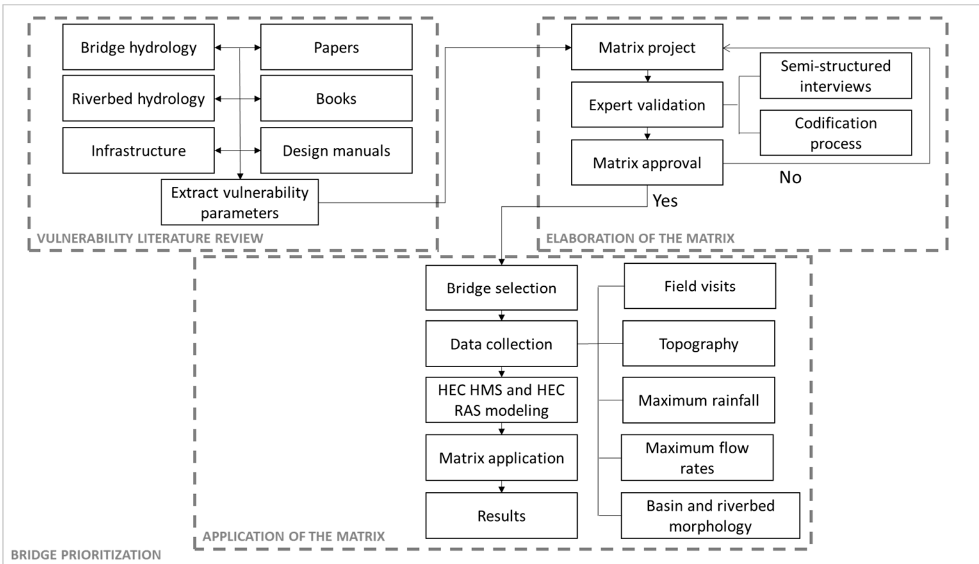

Figure 1. Research methodology.

The study proposes the use of a 1D model in HEC-RAS since it has proven to give reliable results [19-21] and allows the characterization of bridges [22,23], which is important for the analysis and evaluation of common failures such as scour and erosion [24-26]. There are also other programs such as FLO 2D, MIKE 11 and TELEMAC 2D [27,28], where regardless of the program to be used, the input parameters play an important factor [29]. 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, so 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

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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 [30].	135 [31].
P02	Bajo Grau	Restricted to vehicular traffic due to rainfalls in 2012 and 2011 [32,33].	31 [34].
P03	Bolognesi	Bridge in operation since colonial times [32]. Heavy rainfalls weakened its structure [35].	415 [36].
P04	San Martin	Restricted to vehicular traffic due to rainfalls in 2012 and 2011 [32,33].	64 [37].
P05	De Fierro	Restricted to vehicular traffic due to rainfalls in 2019 [38]. It presents problems in one of its ashlar bases [30].	152 [39].
P06	San Isidro	The left side of the bridge is sinking [30].	57 [40].
P07	Tingo	Restricted to vehicular traffic due to rainfalls in 2020 and 2011 [33,41,42].	12 [43].
P08	Bailey	Flooding in areas surrounding the bridge, the National Water Authority reiterated its removal [44]. It was reopened to vehicular traffic [45].	07 [46].

The Figure 2 shows the river section under study, which has a length of 6.95 km from bridge P01 to bridge P08.

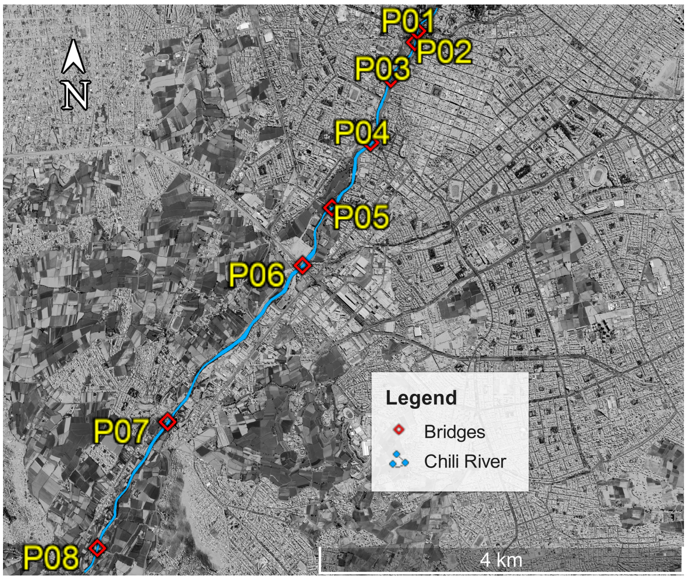
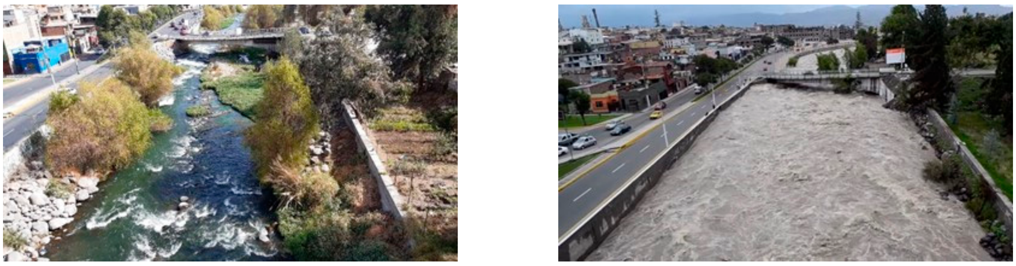


Figure 2. River section under study [47].

Figures 3 and 4 show photographs of three of the eight bridges under study. Bridge P02 is shown during low water levels (Figure 3a) and during a major flood in 2012 (Figure 3b), where the water flow covers the entire width of the channel and impacts the left side of the bridge. Bridge P03 is also shown during the same flood in 2012 (Figure 4a). In addition, Bridge P08 is shown during an upstream flood in 2019 (Figure 4b).



(a) (b)

Figure 3. (**a**) Bridge 02, Bajo Grau, during the low water season; (**b**) Bridge 02, Bajo Grau, during the flood of 2012 [48].

(a) (b)

Figure 4. (**a**) Bridge 03, Bolognesi, during the flood of 2012 [48]; (**b**) Bridge 08, Bailey, during the flood of 2019 [49].

2.3. Literature Review

While erosion, scour and flooding are essential criteria for studying 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 point out criteria for the design of hydrologically safe bridges, which are of special interest to propose an evaluation matrix.

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

ID	Author	Year	Assessment parameters considered in the research
			Main precedent studies
B1	Espinoza & Booker [16].	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. [50].	2021	Social parameters, e.g., the economy of the population, education level and age, as well as safety facilities, shelters, and hospitals.
B4	Glass et al. [51].	2020	Type of housing and current data of the population in terms of economic and social risk.
B5	Garrote et al. [52].	2020	Material of construction of the structure, water depth and flood velocity.
B6	Bento et al. [17].	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 & Baduna [18].	2020	Land use in the basin, surface condition and frequency of flood recurrence.
B8	Julio Kuroiwa [53].	2019	Flow velocity, construction material from nearby houses.
B9	Geng et al. [54].	2019	Flood depth, submerged area and duration of flooding, population density and rate of urbanization.

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B10	Bhatkoti et al. [7].	2016	Climate change and the increase of impervious areas upstream.
B11	Ettinger et al. [55].	2016	Height ranges in terms of flooding, observed damage and soil imperviousness.
B12	Bathrellos et al. [56].	2016	Slope of the study area, permeability, and vegetation cover of the soil.
B13	Mani et al. [57].	2013	Depth and duration of flooding.
	Main Design Codes		
B14	Ministry of Transportation and Communications [58].	2018	Bridge clearance height, material of construction and lifespan.
B15	Ministry of Transportation and Communications [59].	2018	Bridge clearance height.
B16	National Center for Disaster Risk Assessment, Prevention and Reduction [60].	2014	Life span, material, state of infrastructure conservation, material of housing in populated centers and training for residents.
B17	Ministry of Transportation and Communications [61].	2008	Abutment protection, scouring and bridge clearance height.
B18	National Institute of Civil Defense [62].	2006	Climate change, water quality, proximity to population centers and compliance with current regulations.

2.4. 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.

			Environmental Dimension			
ID	**Variable**	**Very low: 1**	**Low: 2**	**Medium: 3**	**High: 4**	**Very High: 5**
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 well above average.
A2	**Water quality**	No degree of contamination.	Low pollution levels.	Moderate level of contamination.	High levels 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.

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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 that 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 meters 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 meters difference between the water surface and the base of the board.	The height allows water to flow normally. It has 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 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%.
			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, participating in drills, being its dissemination	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.

		and total coverage.				
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.	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.	Once the bridge has closed to vehicular traffic due to hydrological risk.	Twice the bridge has closed to vehicular traffic due to hydrological risk.	More than 2 times the bridge has closed due to hydrological risk.
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 are 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 far from the bridge and e) E4: This parameter is applied in case there is no information for parameter E3.

2.5. Matrix Validation

For the validation of the matrix, semi-structured interviews, following guidance in [63], were conducted through digital platforms with 6 bridge hydraulics specialists, informing them that the confidentiality of the interviewees will be assured and that the data collected will be used only for research purposes. The interview procedure had the following order: first, an introduction and general explanation of the research was 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 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?

2.6. 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,

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such as: monitoring over time the performance of the matrix, a vulnerability score range in the results and being careful with the input parameters of the hydraulic model (Table 5). It is concluded that the criteria considered for the evaluation of bridges from a hydrological perspective are sufficient and represent a concrete possibility to analyze a prioritization according to vulnerability in an effective way.

Table 5. Coding of interviews on 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 showing the results in a clear manner. 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 [64], the entity in charge of gauging the flows of the Chili River, were considered to obtain the maximum annual flows and then find the theoretical deltas according to Peruvian regulations [61]. The results are shown in Table 6.

Table 6. Theoretical delta for different types of distribution.

Distribution	Theoretical delta (Ordinary parameters)
Normal	0.0937
Log Normal 2 - parameter	0.1130
Log Normal 3 - parameter	0.0917
Gamma 2 - parameter	0.0807
Gamma 3 - parameter	0.0764
Log Pearson Type III	does not adjust
Gumbel	0.0917
Log Gumbel	0.1761

The Gamma 3-parameter distribution has 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 (m³/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: precipitation, concentration times, initial abstraction, lag time, curve number and impermeability of neighboring gullies [65] 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 the time of concentration of the current basin [66]. This procedure starts from downstream to upstream.

In the modeling of the IDF curves, the Dick Peschke formula was used [61], considering a storm duration of 3 hours, which is equivalent to 180 minutes. For the design, storm profile was elaborated using the Alternating Block Method for the streams studied every 10 minutes. For the hydrological modeling, the data obtained were entered using the SCS Curve Number model as Loss Method and the SCS Unit Hydrograph model as Transform Method. A computational interval of 1 minute 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 (m³/s)**		
	Return period (years)		
	100	**200**	**500**
P 01. 02. 03 y 04	388.42	442.24	590.50
P 05 y 06	406.32	466.14	623.30
P 07 y 08	476.52	543.04	766.10

Considering a safety margin in terms of risk for the bridges, it was considered convenient to use a return period of 500 years (useful life of 75 years and a risk of 14%) for the hydraulic modeling due to the importance of the bridges under study. Likewise, the flow rates used were calibrated with videos of a maximum flood that occurred in 2012, obtaining similarity in the maximum water levels, thus corroborating an optimal model. The modeling flow rates were then obtained: for bridges P01, P02, P03 and P04, 590.5 m³/s; for bridges P05 and P06, 623.3 m³/s and 766.1 m³/s for 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 [67]. 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 [68], thus having an adequate topography for hydraulic modeling. The 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.

3.3. Hydraulic Modeling

A 3D view from HEC-RAS of bridges P01, P02, P03 (Figure 5), P04, P06, P07 and P08 (Figure 6) is shown. Bridge 05 was not modeled because it is not floodable due to its high height. The results of the Extraordinary Maximum Water Levels (EMWL) served for the analysis of the vulnerability of the bridges using the proposed assessment matrix.

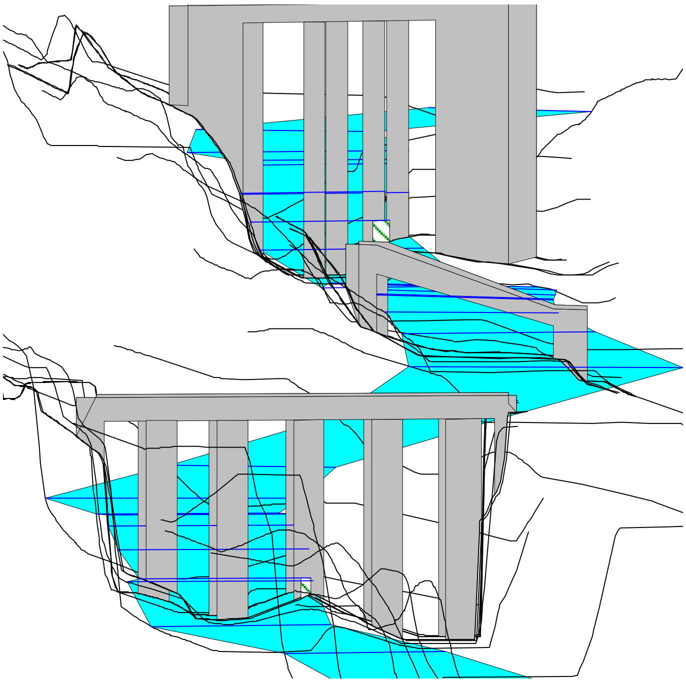

Figure 5. 3D Hydraulic Modeling View of Bridges 01, 02 and 03 (upstream to downstream).

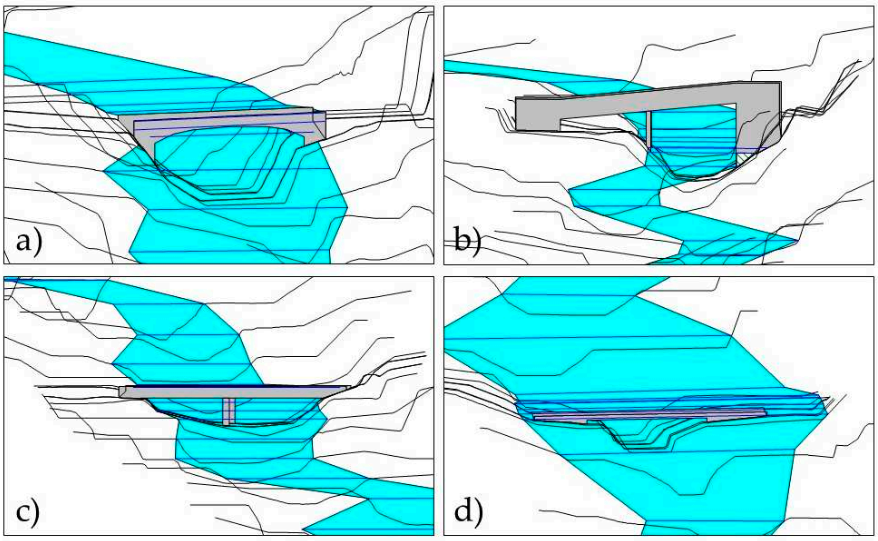

Figure 6. 3D Views of Bridge Hydraulic Modeling a) Bridge 04, b) Bridge 06, c) Bridge 07, d) Bridge 08.

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 favored 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 and due to 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 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, 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 response to hydrological events. They mentioned that eventually the municipality cleans the riverbed.	4
S3	It was observed that the population lives less than 0.2 kilometers away.	5
S4	The houses are made of brick masonry.	1
E1	The bridge was inaugurated on August 11, 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, only the E4 parameter is 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

Being 2.5 half of the maximum vulnerability assessment value, bridges with an average score of less than 2.5 are considered with a low vulnerability, those with values greater than 2.5 and less than 3, medium vulnerability, and those greater than 3, high vulnerability. 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, subdivided into 4 dimensions: environmental, technical, social, and economic. A total of 18 evaluation parameters were considered, distributed as follows: 4 environmental, 6 technical, 4 social and 4 economic parameters. Each parameter has 5 evaluation levels: very low, low, medium, high, and very high, with values between 1 and 5 respectively. To find the final weighting, the scores of the parameter evaluations were averaged. Bridges with an average greater than or equal to 3 were considered high vulnerability bridges, between greater than or equal to 2.5 and less than 3 as medium vulnerabilities, and less than 2.5 as low vulnerability. The matrix was validated by 6 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 8 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 bridges evaluations.

The vulnerability of the bridges was determined through a 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, 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 an analysis were used to estimate the modeling flow rates and a flow rate of 590.5 m3/s was obtained for bridges 01, 02, 03 and 04; 623.3 m3/s for bridges 05 and 06 and for bridges 07 and 08 a flow rate of 766.1 m3/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 find the EMWL of each bridge, obtaining as results 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 providing hthe 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 the knowledge of what infrastructure is 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. Now, 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, from a multidimensional analysis, contributes to generate a sense of urgency regarding the state of the bridges and the risk they represent for their users, so that, effectively, their intervention is prioritized.

With regard to the evaluation, there are additional parameters that could be integrated to 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 founded. 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 the extreme events.

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 interventions are effectively applied to a series of bridges, assessing their impact on the infrastructure and society.

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