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Framework for assessing flood-induced bridge performance considering climate change

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Abstract. *As the frequency and intensity of extreme rainfall increase due to climate change, flood-induced hazards pose a growing threat to the structural integrity of bridge systems. While considerable research has addressed changes in flood magnitude associated with climate scenarios, relatively few studies have focused on the performance assessment of bridges under such conditions. This study proposes a comprehensive framework for evaluating bridge system performance under flood hazards, incorporating the influence of climate change. The framework integrates climate projection data, hydrological modeling, hydraulic analysis, structural simulation, and reliability assessment. First, probabilistic rainfall intensities for various durations are derived using Representative Concentration Pathways scenarios provided by the Intergovernmental Panel on Climate Change, combined with a conditional copula model and frequency analysis using FARD2006. Second, the HEC-HMS model is used to simulate flood discharges based on probabilistic rainfall and HEC-RAS is employed to simulate flow velocity, water surface elevation. Finally, the probability of bridge failure is evaluated using fragility curves developed through a Python-based interface linking FERUM (Finite Element Reliability Using MATLAB) and ABAQUS, and the failure probabilities were derived under various climate change scenarios to account for the effects of future flood hazards on structural performance. The proposed framework is demonstrated through a case study of the Jungnangcheon river watershed in Seoul, South Korea. The findings offer practical insights for updating bridge design standards and developing maintenance strategies in the face of evolving climate risks.*

1 INTRODUCTION

With the increasing frequency and intensity of extreme rainfall due to climate change, critical infrastructure such as bridges is becoming more vulnerable to flood-induced structural risks. Floods triggered by extreme precipitation can lead to rapid increases in flow velocity and water depth, resulting in elevated hydraulic loads that may significantly increase the probability of bridge failure.

Numerical efforts have been made to evaluate flood discharge under climate change scenario. Morita [1] demonstrated that climate change would lead to an increase in rainfall and flood volumes, resulting in higher flood risk in urban areas. Bai et al. [2] utilized climate scenarios from the Coupled Model Intercomparison Project Phase 5 (CMIP5) to estimate future flood discharges for various return periods, demonstrating that higher emission scenarios lead to significantly increased flood magnitudes. Thakur et al. [3] simulated hydrologic and hydraulic responses for an observed rainfall event and suggested that more intense and shorter-duration rainfall could lead to greater flood inundation in the future.

In addition, several studies have investigated the structural performance of bridges under flood conditions. Lee et al. [4] developed a flood fragility analysis framework for bridges by integrating finite element modeling with structural reliability analysis, considering hydraulic loads and material deterioration. Kim et al. [5] conducted a flood fragility analysis of a bridge using finite element reliability analysis, incorporating multiple failure modes including deck drop, pier rebar rupture, and pile ductility loss under flood-induced loads such as water pressure, debris accumulation, and scour.

While numerous studies have independently examined the increase in flood magnitudes and the probability of bridge failure under flood conditions, research that quantitatively evaluates bridge vulnerability to flooding in the context of climate change remains limited. To address this gap, the study proposes an integrated framework for quantifying the failure probability of bridges subjected to flood hazards considering climate scenarios. The proposed framework comprises three interrelated modules: (1) precipitation analysis based on climate change, (2) hydrologic and hydraulic modeling, and (3) structural reliability assessment. These modules are systematically integrated to estimate the probability of bridge foundation failure by accounting for hydrostatic load, hydrodynamic load and scour effects induced by flood conditions associated with projected extreme rainfall events.

The remainder of this paper is organized as follows. Chapter 2 describes the structure of the proposed framework and the details of each module. Chapter 3 presents the application to a bridge model and summarizes the analysis results. Chapter 4 presents the application results and limitations of the proposed framework, and outlines directions for future research.

2 FRAMEWORK FOR FLOOD-INDUCED BRIDGE VULNERABILITY

2.1 Overview

This study proposes an integrated framework for probabilistically assessing the structural vulnerability of bridges under rainfall scenarios driven by climate change. The proposed framework consists of three interconnected modules (precipitation analysis, hydrologic and hydraulic analysis, and structural reliability assessment) each of which is designed to reflect the uncertainty in both environmental loading and structural response. Figure 1 illustrates the overall analytical flow of the framework.

The first module involves Representative Concentration Pathways (RCPs) provided by the Intergovernmental Panel on Climate Change (IPCC). Annual maximum daily rainfall data corresponding to different RCP scenarios are collected, and a conditional copula model is used to generate rainfall intensities across various durations.

In the second module, hydrologic and hydraulic analyses are conducted using an integrated approach with HEC-HMS (Hydrologic Engineering Center – Hydrologic Modeling System) and HEC-RAS (Hydrologic Engineering Center – River Analysis System). The rainfall data derived from the first module are input into HEC-HMS to estimate flood discharges for various return periods, reflecting the watershed's response to future extreme precipitation. These discharge results are then used in HEC-RAS to compute water surface elevations and flow velocities at critical river cross-sections, which serve as boundary conditions for the subsequent structural analysis.

The third module is structural reliability assessment, which utilizes a Python-based interface linking FERUM (Finite Element Reliability Using MATLAB) and ABAQUS (PIFA). The simulated hydraulic conditions (specifically water levels and velocities) are input into this interface to perform reliability analysis of the bridge under uncertain structural parameters. Fragility functions are developed to estimate the probability of failure under each rainfall scenario.

The following sections provide a detailed description of each module within the proposed framework.

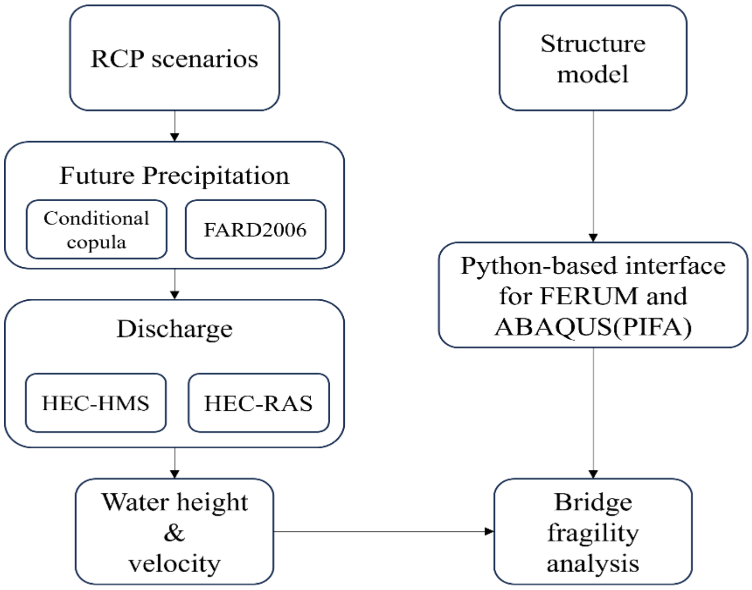

Figure 1: Integrated framework for bridge fragility analysis under climate change scenarios

2.2 Precipitation analysis

2.2.1 Obtaining high resolution precipitation analysis

A variety of General Circulation Models (GCMs) are available for simulating climate scenarios. However, their coarse spatial resolution and inability to capture localized climate variability make them unsuitable for direct application in regional hydrologic or structural analyses [6]. To address these limitations, downscaling techniques (either statistical or dynamical) are commonly used to refine GCM outputs for regional applications. In this study, climate projections were obtained from a Regional Climate Model (RCM), which dynamically downscales GCM boundary conditions to generate high-resolution climate information that incorporates detailed topography and better reflects regional precipitation patterns [7, 8].

Among the available RCMs, this study employed the HadGEM-RA model, which is a dynamically downscaled version of the HadGEM2-AO global model developed by the UK Met Office Hadley Centre. HadGEM2-AO is one of the standard models in the CMIP5 framework and has demonstrated high performance in simulating global and East Asian climate characteristics under various RCP scenarios. It has shown particularly strong skill in reproducing regional changes in temperature and precipitation, making it a reliable tool for climate impact assessments in Korea [9].

2.2.2 Preprocessing of precipitation data

The annual maximum daily precipitation obtained in Section 2.2.1 represents the total rainfall accumulated over a 24-hour period. However, as previously mentioned, the hydrologic simulation model HEC-HMS requires probabilistic rainfall inputs for various shorter durations such as 1-hour and 3-hour events. To address this, the present study employed a two-step procedure to construct duration-specific design rainfall data and derive probabilistic rainfall values for hydrologic modeling. In the first step, rainfall amounts for various durations are estimated based on the 24-hour precipitation data. In the second step, these estimates are subjected to frequency analysis using the FARD2006 (Frequency Analysis of Rainfall Data 2006) program to obtain probabilistic rainfall for each duration.

According to the method developed by Kim et al. [10], conditional Archimedean copulas are introduced to model the probabilistic dependence between 24-hour and sub-daily extreme rainfall. Their approach enables the estimation of short-duration rainfall by reproducing the conditional distribution given a known 24-hour total. In this method, the marginal cumulative distribution functions (CDFs) of short-duration rainfall X and 24-hour rainfall Y are assumed to follow the Gumbel distribution, with parameters estimated via maximum likelihood.

The method is based on Sklar's theorem, which allows the joint cumulative distribution of two variables to be decomposed into their marginal distributions and a copula function that captures their dependence structure. According to Sklar's theorem, the joint distribution $F_{X,Y}\ (x,y)$ is expressed as:

$$F_{X,Y}\ (x,y) = C\big(F_X(x), F_Y(y)\big) \tag{1}$$

where $F_X(x)$, $F_Y(y)$ are the marginal cumulative distribution functions of X and Y. $C(\cdot)$ is the selected copula function that captures the dependence structure between X and Y. The transformed variables $u = F_X(x)$ and $v = F_Y(y)$ represent the cumulative probabilities of x and y, and are constrained to the unit interval $[0, 1]$.

Given a specific 24-hour rainfall value $Y = y$, the conditional cumulative distribution of X can be obtained by differentiating the copula function with respect to the second argument v. This yields the conditional cumulative probability as:

$$P(X \leq x | Y = y) = \left.\frac{\partial C_\theta(u,v)}{\partial v}\right|_{v=F_Y(y)} \tag{2}$$

where θ is the dependence parameter of the copula, which governs the strength and direction of the association between the two variables. The value of θ is typically estimated from data using methods such as maximum likelihood estimation (MLE) and varies depending on the copula family used (e.g., Gumbel, Clayton, Frank).

In this study, a bivariate Archimedean copula is used, which is defined in terms of a generator function $\varphi(t)$ as:

$$C(u, v \mid \varphi) = \varphi\left(\varphi^{-1}(u) + \varphi^{-1}(v)\right) \tag{3}$$

The generator function $\varphi(t)$ is strictly decreasing, convex, and satisfies the boundary condition $\varphi(1) = 0$. Differentiating the copula with respect to v results in the conditional copula form known as the h-function:

$$h(u|v) = \frac{\varphi'\left(\varphi^{-1}(u) + \varphi^{-1}(v)\right)}{\varphi'\left(\varphi'(v)\right)} \tag{4}$$

where φ' is the first derivative of the generator function $\varphi(t)$.

Given a 24-hour rainfall value y, its cumulative probability v is first computed. Then, a conditional cumulative probability $p = h(u|v)$ is sampled. The corresponding short-duration rainfall amount x is obtained by inverting the h-function as follows:

$$h^{-1}(u; v, \varphi) = \varphi(\,(\varphi')^{-1}(\,u\,\varphi'(\,\varphi^{-1}(v))) - \varphi^{-1}(v)) \tag{5}$$

Subsequently, probabilistic rainfall estimates were derived using the duration-specific rainfall data obtained through the conditional copula approach.

For the frequency analysis of rainfall, the FARD2006 program developed by the National Disaster Management Research Institute of Korea was employed. FARD2006 supports parameter estimation based on various methods such as the method of moments, maximum likelihood estimation, and probability-weighted moments. It also provides goodness-of-fit test results for each distribution, allowing users to assess statistical suitability with ease. Due to its usability and reliability, it is widely used for rainfall frequency analysis in Korea [11].

2.3 Hydrologic and hydraulic analysis

HEC-HMS is a hydrologic modeling system developed by the U.S. Army Corps of Engineers, commonly used for simulating continuous hydrologic processes and flood events. It has demonstrated flexibility and broad applicability in rainfall-runoff modeling, flood frequency analysis, and urban drainage design across a wide range of watershed conditions [12,13]. In recent years, HEC-HMS has also been actively used in studies that estimate future flood discharges based on rainfall data derived from climate change scenarios [2, 14].

HEC-RAS, also developed by the U.S. Army Corps of Engineers, is a hydraulic modeling tool widely used for simulating open channel flow and flood routing. The model calculates key hydraulic parameters such as water surface elevation, flow velocity, and Froude number under steady or unsteady flow conditions [3, 14]. It has been applied in various flood modeling studies under different climatic and land use scenarios, proving its reliability and effectiveness [15,16].

In this study, the probabilistic rainfall derived from climate change scenarios in Section 2.2 was applied to the HEC-HMS model of the target watershed to estimate flood discharges. The resulting discharge values were then input into the HEC-RAS model to simulate the flow velocities and water surface elevations required for subsequent analyses. These hydrologic and hydraulic outputs were used as input data in the proposed framework to determine bridge failure probabilities under each scenario

2.4 Bridge failure analysis

In this study, the flood-induced fragility analysis of a target bridge originally conducted based on hydraulic forces and scour under the finite element reliability framework of Kim et al. [5] is extended by incorporating hydrostatic pressure as an additional failure mechanism. This framework quantifies the probability of structural damage exceeding specific limit states under given hydraulic loading and deterioration conditions by deriving fragility curves. In this study, displacement ductility is adopted as the primary failure criterion for evaluating bridge performance under flood conditions.

Displacement of ductility demand (M_D) is defined according to the ratio of the imposed post-elastic deformation. M_D is expressed as [17]:

$$M_D = \frac{\Delta_D}{\Delta_{Y(i)}} \tag{6}$$

where Δ_D is the maximum displacement of a structural member and $\Delta_{Y(i)}$ is the displacement at the yielding point of the member. The limit-states of displacement ductility are defined as the three damage states (minor damage, major damage, and collapse) as shown in Table 1 [18,19]. This study focuses on minor damage.

Table 1: Damage states and corresponding ductility demands

Damage state	Ductility demand
Minor damage	$1.0 \leq D_d \leq 3.3$
Major damage	$3.3 < D_d \leq 7.0$
Collapse	$D_d > 7.0$

The analysis considers two hydraulic loads (hydrodynamic pressure (p_D) and hydrostatic pressure (p_S)) as direct external forces, while scour is treated as a geotechnical factor that alters the boundary conditions of the bridge foundations. Hydrodynamic pressure, induced by the velocity of floodwater, was calculated according to AASHTO [20] and KHBDS (Korean Highway Bridge Design Specification) [21] and applied laterally to the substructure. Hydrostatic pressure was modeled as a linearly increasing pressure distribution with water depth and applied vertically on the submerged surfaces. Scour was estimated using the empirical equation proposed by Yanmaz [22] and implemented by progressively removing spring supports in the pile model according to the calculated scour depth (S). This approach simulates the reduction in geotechnical resistance caused by erosion around the foundation. p_D, p_S, S is expressed as:

$$p_D = 5.14 \times 10^{-4} C_D V^2 \tag{7}$$

$$p_S = \rho g h \tag{8}$$

$$S = 1.564 \times x^{0.405} \times \left(\frac{V}{\sqrt{g \times h}}\right)^{0.413} \tag{9}$$

where C_D is the drag coefficient which can be determined from pier type, V is the water velocity, ρ is density of water, g is the gravitational acceleration, x is the relative approach flow depth, and h is the depth of the approach flow.

Nonlinear structural responses were computed using ABAQUS, incorporating the nonlinear stress–strain behavior of concrete and reinforcing steel. To account for uncertainties in loading and material properties, reliability analysis was performed using FERUM, applying the First Order Reliability Method (FORM) to compute the reliability index β, and the failure probability was approximated as $P_f \approx \Phi(-\beta)$ [23]. The entire analysis process was automated via a Python-based interface linking ABAQUS and FERUM [4].

Based on the analysis results, the failure probability of the bridge will be evaluated under different water levels and flow velocities for each climate scenario, and the outcomes will be compared and analyzed accordingly.

3 NUMERICAL EXAMPLE

3.1 Study area

This study focuses on the Jungnangcheon river watershed, located in the northern region of Gyeonggi-do, South Korea, and within the Han River basin. The watershed covers an area of approximately 118.86 km², with a stream length of about 15.86 km and an average width of roughly 7.49 km. The downstream region of the watershed is highly urbanized and densely populated, while the upstream area is characterized by mountainous terrain interspersed with agricultural land and small settlements. In particular, the high level of urbanization in the downstream area significantly increases potential flood damage and economic losses, underscoring the importance of assessing flood risks under climate change scenarios.

3.2 Precipitation analysis

This section presents the application of the previously constructed conditional copula model to estimate design rainfall for various return periods under future climate scenarios. Future precipitation data were collected from the HadGEM3-RA model provided by the Korea Meteorological Administration, covering annual maximum daily rainfall for the period 2021–2100. Figure 3 illustrates the Precipitation data for the RCP scenarios. To support the development of duration-specific rainfall scenarios, historical rainfall data with durations ranging from 1 to 24 hours were obtained from the Water Resources Management Information System (WAMIS) for the years 1978–2017.

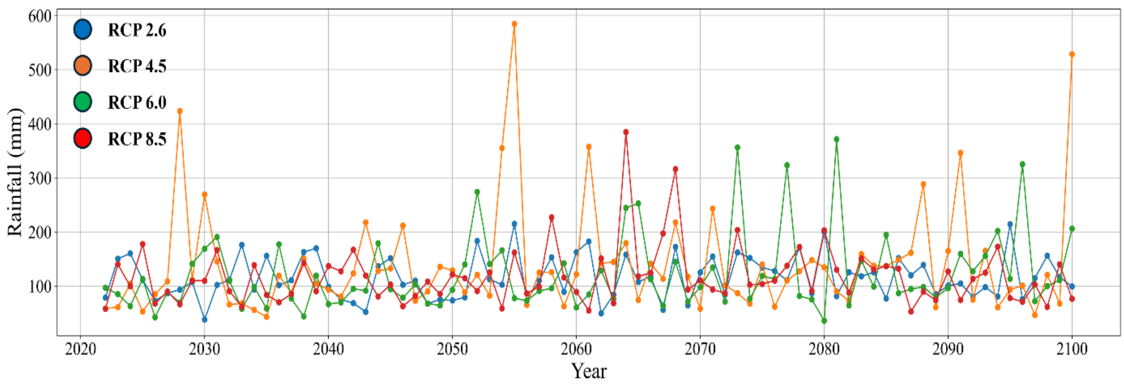

Figure 3: Precipitation Data under Different RCP Scenarios

Figure 4 shows a comparison between the actual measured data and the copula model output for 12-hour and 24-hour durations. In this study, the RSR (RMSE-to-standard deviation ratio) was used to evaluate the performance of the conditional copula model. According to Moriasi et al. [24], an RSR value between 0.50 and 0.60 indicates good performance, between 0.60 and 0.70 indicates satisfactory performance, and values above 0.70 are considered unsatisfactory. The average RSR value derived from the duration-specific rainfall data in this study was approximately 0.64, indicating that the model performance falls within the satisfactory level.

These rainfall data were then input into the FARD2006 program to compute probabilistic rainfall corresponding to various return periods

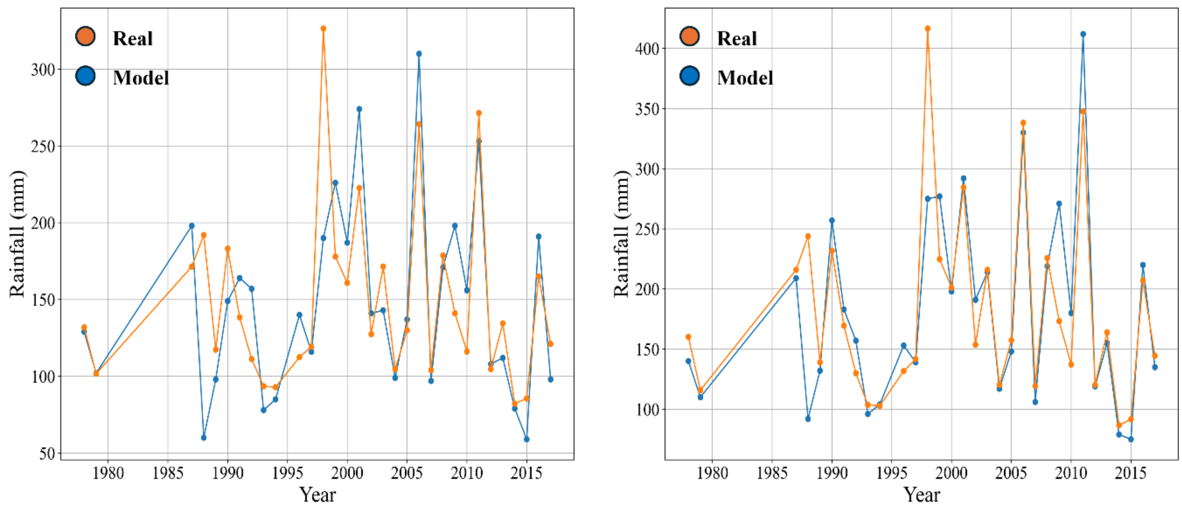

Figure 4: Comparison of observed and predicted rainfall for 12-hour (left) and 24-hour (right) durations

3.3 Hydrologic and hydraulic analysis

After estimating the flood discharges for various return periods in Section 3.2, a hydrologic model of the Jungnangcheon river watershed was developed using HEC-HMS. The input parameters were based on the MLIT [25]. The simulated flood discharges for each return period are summarized in Table 2.

Subsequently, these flood discharge results were input into the constructed HEC-RAS model to simulate flow velocities and water surface elevations. For computational efficiency and rapid analysis. The simulated velocities and water surface elevations obtained from the HEC-RAS model are also summarized in Table 2.

Table 2: Hydraulic and hydrologic result

	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5
Discharge (m^3/s)	1148.5	1315.9	1257.3	1243.0
Water velocity (m/s)	7.78	8.14	8.02	7.99
Water height (m)	6.15	6.74	6.53	6.48

3.4 Bridge failure analysis

In this study, to derive the bridge failure curve, the bridge model used is as shown in Figure 5, and the statistical properties are summarized in Table 3 [5].

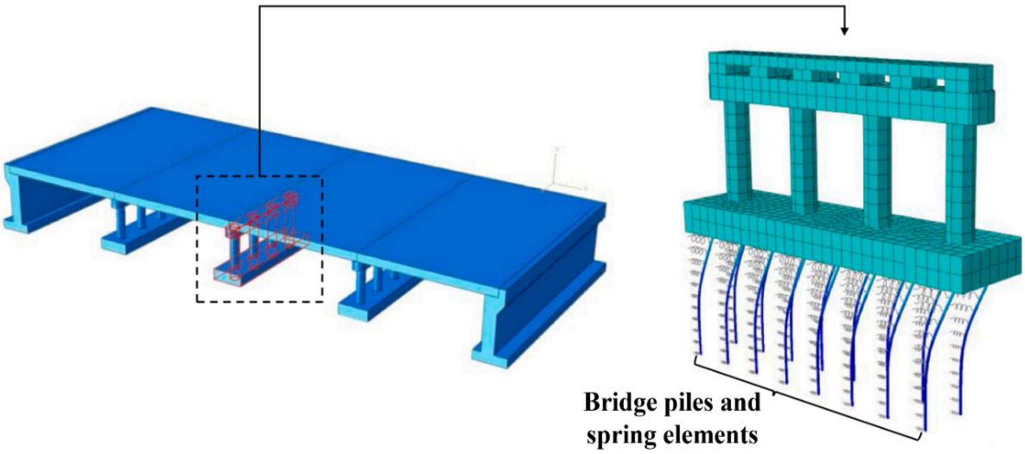

Figure 5: ABAQUS model for bridge structure and pier

Table 3: Statistical properties of random variables for bridge failure analysis

	Distribution type	Mean	COV
Concrete mass density (kg/m^3)	Normal	2300	0.3
Steel bar mass density (kg/m^3)	Normal	7861.5	0.3
Pile steel mass density (kg/m^3)	Normal	7868.6	0.2
Water pressure intensity scale factor	Normal	1.0	0.1

Figure 6 presents the bridge failure curve under minor damage conditions with respect to flow velocity and water depth. As observed in the figure, the failure probability increases sharply with rising velocity and depth. This result indicates that, under extreme flood conditions, the structural stability of bridges deteriorates rapidly due to increased hydrodynamic forces, hydrostatic pressure, and scour effects.

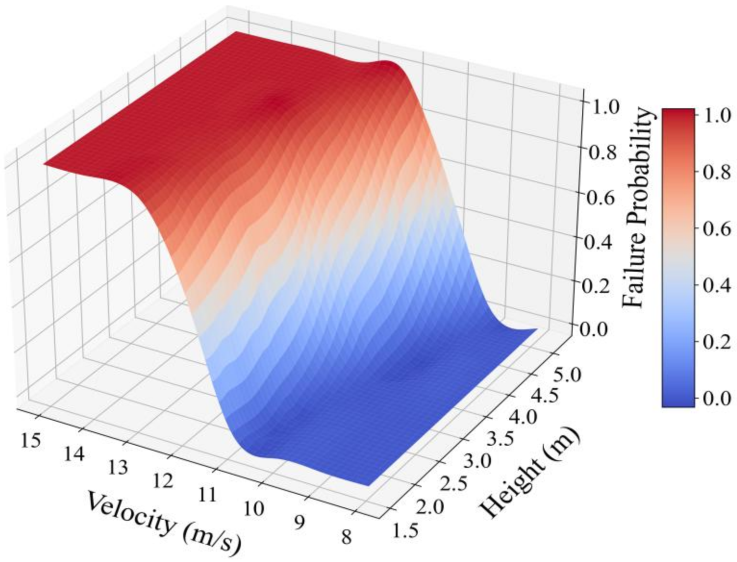

Figure 6: Bridge failure probability graph at minor damage

In this study, the 100-year return period flood (corresponding to a 1% annual exceedance probability) was selected as the design flood event, following the guidelines provided by FEMA [26]. According to the manual, the base flood, defined as the flood with a 1% chance of being equaled or exceeded in any given year, is commonly adopted as the minimum regulatory design flood under the National Flood Insurance Program (NFIP), and is widely used for structural design and flood risk management in coastal areas. Table 4 summarizes the bridge failure probabilities at minor damage corresponding to the 100-year return period flood under each RCP scenario, based on the associated flow velocity and water depth.

Table 4: Bridge failure probabilities at minor damage

Failure probability	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5
Minor damage	0.1145	0.2378	0.1858	0.1745

According to the results, bridge failure probabilities are highest under the RCP 4.5 scenario, followed by RCP 6.0, RCP 8.5, and RCP 2.6. As shown in Figure 3, this pattern appears to be due to the greater variability in rainfall under the RCP 4.5 and 6.0 scenarios. Increased variability in rainfall leads to larger flood volumes caused by extreme precipitation, which in turn raises the probability of bridge failure. Therefore, it is confirmed that this variability is the primary reason for the observed results [27].

4 CONCLUSIONS

This study developed an integrated framework to assess the flood-induced fragility of bridges under future climate scenarios. The framework incorporates a conditional copula model to estimate sub-daily rainfall based on HadGEM3-RA projections and historical data, followed by frequency analysis using FARD2006. These rainfall estimates were input into HEC-HMS and HEC-RAS to simulate flood discharges and hydraulic responses, which were used in a finite element-based structural reliability analysis. Bridge failure probabilities were assessed across RCP scenarios, with the highest found under RCP 4.5, possibly due to nonlinear regional rainfall variability and internal climate fluctuations.

One limitation of this study is that bridge failure probabilities were primarily observed under very high flow velocity conditions, which may not fully represent typical flood scenarios. To address this, future research should consider a wider range of hydraulic loading conditions beyond extreme flows. Furthermore, future research will expand beyond bridge failure probabilities to incorporate traffic network analysis, assessing the broader impacts of bridge collapse on regional transportation systems.

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