

Real Time Hydraulic Bridge Elevation Control System for Enhanced Flood Resilience and Transport Safety

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Abstract: Flood-induced bridge failures remain a major challenge for transportation infrastructure in flood-prone regions. Conventional fixed bridges are highly vulnerable to hydrodynamic forces, scour, debris accumulation, and deck submergence during extreme flood events. This research proposes an automated hydraulic elevating bridge system capable of dynamically adjusting bridge deck elevation in response to real-time river water levels. The proposed system integrates ultrasonic water-level sensing, an ESP32-based control unit, hydraulic actuators, and an intelligent control algorithm to ensure uninterrupted transportation during flooding conditions. Structural and hydraulic design parameters were evaluated through analytical calculations and simulation studies. The developed prototype demonstrated reliable operation, rapid response, and effective elevation control under simulated flood scenarios. The proposed approach offers enhanced flood resilience, improved public safety, reduced maintenance costs, and increased infrastructure adaptability under climate-change-induced flood events.

Keywords: Flood resilience, Hydraulic bridge, Smart infrastructure, ESP32, Water level monitoring, Adaptive bridge system.

INTRODUCTION

Conventional bridges in flood-prone areas are often vulnerable to damage and failure due to their inability to adapt to sudden increases in river water levels. Flood events can cause bridges to become unsafe and inaccessible, significantly impacting transport and safety in affected regions. Floodwaters exert several types of damaging forces on bridges. These include hydrodynamic forces from fast-moving water, debris impact from floating objects like logs and vegetation, and scouring and erosion around bridge foundations. Scouring—the removal of sediment around piers and abutments due to increased water velocity—is a leading cause of bridge failure in floods as it undermines foundation stability. Additionally, debris accumulation can block water flow, increase upstream pressures, and amplify scour effects, collectively threatening structural integrity. Submerged bridge decks experience increased static water pressure and horizontal forces, which can lead to deck failure. Many catastrophic bridge failures worldwide have been linked to flood-related issues such as hydrodynamic overload, debris impact, erosion, and scour. Examples include multiple bridge collapses and damages in places like Japan, China, Australia, and the USA during recent severe floods. These failures

highlight the necessity for flood-adaptive bridge design and heightened maintenance and monitoring practices.

Components of such a design include:

Hydraulic Actuation System: Comprising hydraulic cylinders, pumps, and control valves capable of smoothly and reliably lifting the bridge span vertically. The system must be robust enough to handle the weight of the superstructure and dynamic loads during elevation changes.

Water Level Sensing and Control: Installation of precise sensors (e.g., radar, ultrasonic) to continuously monitor river water levels and an automated control unit that triggers the

hydraulic system based on predefined safety thresholds.

Structural Adaptation: Designing the bridge superstructure and substructure to accommodate vertical movement without compromising stability or durability. This may involve telescoping piers or adjustable bearing systems that allow movement while maintaining load transfer.

Safety and Redundancy: Implementing fail-safe features, backup power supplies, and emergency manual override capabilities to ensure operational reliability

during critical flood events.

Environmental and Economic Considerations:

Assessing the bridge's ecological footprint and life-cycle costs, ensuring that the technology is sustainable and economically viable for flood-prone regions.

Objectives

1. Analyze river water level patterns and flow conditions that impact bridge safety.
2. Design a hydraulic mechanism that automatically adjusts the bridge elevation in response to changing water levels.
3. Implement a sensor-driven monitoring system for real-time detection and automated control.
4. Evaluate the structural performance, reliability, and maintenance needs of the hydraulic bridge under diverse flood scenarios

Scope of the Project Work:

The scope of this project is to design and develop a hydraulic bridge mechanism capable of automatically adjusting its elevation in response to real-time changes in river water levels. The primary aim is to ensure uninterrupted transportation and enhance flood safety in flood-prone areas where conventional bridges face accessibility and structural risks due to rising water levels.

Expected outcome

The expected outcome of this project is the successful design and development of a hydraulic bridge mechanism capable of automatically adjusting its elevation in real-time based on rising river water levels. This system aims to ensure continuous and safe transportation during flood events, significantly reducing the risk of bridge submergence, structural damage, and accessibility disruptions.

- **Enhanced Flood Resilience:** The bridge will dynamically elevate above floodwaters, preventing damage caused by submersion, debris impact, and scour, thus extending the lifespan of the infrastructure.
- **Uninterrupted Connectivity:** By maintaining operability during floods, the bridge will support uninterrupted movement of vehicles and pedestrians, which is critical for emergency response, commerce, and daily commuting.
- **Increased Safety:** Automated elevation adjustments based on sensor data will minimize accident risks

associated with flooded or unsafe bridge conditions.

- **Reduced Maintenance and Repair Costs:** Avoiding flood damage helps lower longterm expenses associated with repairs, emergency closures, and reconstruction.
- **Technological Advancement:** The project will demonstrate integration of hydraulic systems, sensor technology, and automated control in civil infrastructure, paving the way for smarter, adaptive bridges.
- **Prototype Validation:** A functional prototype or simulation will validate system reliability, response time, and robustness under different flood scenarios, providing valuable data for future improvements.
- **Contribution to Climate Adaptation:** This adaptive bridge design aligns with global efforts to create infrastructure resilient to climate change impacts such as increasing flood frequency and intensity.

LITERATURE REVIEW

Tatsunori Hiramoto, Riku Kubota, Jin Kashiwada, Mayumi Mizuno, Koji Nishi, Mamoru Tanaka, Yasuo Nihei, International Journal of Disaster Risk Reduction, 2025, "Relationship between vehicle probe data and flooding conditions for developing flood inundation monitoring method"

Heavy rainfall disasters caused by climate change have become increasingly severe and frequent causing extensive flood damage worldwide. This study aims to clarify the relationship between vehicle traffic information obtained from vehicle probe data and actual flood inundation conditions for real-time flood inundation monitoring. The results show that the presence or absence of vehicle traffic area corresponds to the expansion or contraction of the inundation area during flooding, verifying the validity of inundation area estimation using vehicle traffic information. The results indicate a negative correlation between vehicle speed, flow velocity, and inundation depth suggesting vehicle speed is an important indicator to understand flood inundation conditions.

Shan-e-hyder Soomro, Huaibin Wei, Muhammad Waseem Boota, Nishan-E-hyder Soomro, Muhammad Faisal, Sana Nazli, Soraya sarwari, Xiaotao Shi, Caihong Hu, Jiali Guo, Yinghai Li, Ecological Informatics, 2025, "River basin urban flood resilience: A multi-dimensional framework for risk mitigation to adaptive management and ecosystem protection under changing climate"

This study aims at the Kunhar River Basin, Pakistan that has been facing repeated flood occurrences on a recurring basis. A system of flood susceptibility mapping is developed based on Geographic Information Systems (GIS), Principal Component Analysis (PCA), and Support Vector Machine (SVM) classification. Four kernel functions were applied and the highest-performing was the Radial Basis Function (SVM-RBF). The model was validated and trained using historical flood inventories, morphometric parameters, and hydrologic variables with feature dimensionality reduced via PCA for increased efficiency. The SVM-RBF model recorded an AUC of 0.8341, 88.02% success, 84.97% predictability, 0.89 Kappa value, and F1-score of 0.86 indicating high predictability. The results support the superiority of the SVM-RBF approach compared to conventional bivariate methods in modeling flood susceptibility over complex terrain of mountains.

Thomas Lucaora, Antonio Annis, Fernando Nardi, Maria Cristina Rulli, Davide Danilo Chiarelli, Agricultural Water Management, 2025, "Distributed hydrodynamic modelling for assessing flood impacts on crops: Assessing flood-resilient crop management in a coastal basin of central Italy"

Nuisance flooding phenomena affect not only urban areas but also agriculture determining catastrophic damages to crops. This work proposes a quantitative physically based method for crop damage assessment based on distributed hydrodynamic modelling of flood events. It exploits a combined high-resolution 1D-2D hydraulic model and crop resistance interlinked dynamics. The methodology allows to quantify with unprecedented high resolution the spatially distributed probability of crop losses for different crop types for different flood recurrence intervals. Results showed that April is the most vulnerable month with greatest potential losses due to high concentration of winter cereals with high fragility at the flowering stage. Alternative crops demonstrate to be more flood tolerant showing the potential use of the proposed methodology towards better agricultural management in floodplains.

Ehsan Haghghi, Ahmad Kasraei, Stephen Famurewa, Gustav Strandberg, Gabriel Sas, A.H.S Garmabaki, Sustainable Cities and Society, 2025, "Climate change risks on railway infrastructure: A systematic review and analysis"

As critical infrastructure, railways are highly vulnerable to climate hazards intensified by climate change.

However, awareness of these risks is low and comprehensive studies outlining these hazards and their impacts on railways are scarce. To address these gaps, this review aims to identify climate-related risks, clarify the hazard-impact relationships and risk interconnections, and explore strategies to account for the influence of climate change on these risks. A systematic literature review was conducted resulting in 71 peer-reviewed papers. As a result, 24 climate hazards and 29 associated impacts were identified and categorized. The hazards and impacts having the most and least occurrence in the literature were highlighted. Informative matrices were developed to correlate hazards with impacts and illustrate the cascading effects of the impacts. Four distinct approaches used to address the effects of climate change on climate risks were identified and critically discussed. The study highlights critical gaps in the literature to guide future research.

RESEARCH METHODOLOGY

The proposed hydraulic bridge mechanism is an innovative infrastructure solution designed to enhance flood resilience by automatically adjusting the bridge's elevation in real-time in response to rising river water levels. The system integrates advanced sensor technologies for precise water level monitoring, a robust microcontroller-based control unit for intelligent decision-making, and a high-capacity hydraulic actuation system capable of smoothly lifting and lowering the bridge deck. This adaptive feature ensures continuous, safe access across the river during flood events, minimizing disruption and potential damage compared to conventional fixed bridges.

System Architecture and Components

- **Water Level Sensing Subsystem:** Utilizes ultrasonic or radar sensors strategically positioned upstream to provide accurate, continuous measurements of the river stage, with calibration to local hydrological parameters.
- **Control and Processing Unit:** Employs a programmable microcontroller or PLC capable of processing sensor data, executing control algorithms, managing safety protocols, and communicating system status to operators.
- **Hydraulic Actuation System:** Includes high-strength hydraulic cylinders, pumps, valves, and fluid reservoirs engineered for durability and rapid response, designed to carry the full bridge deck load and dynamic flood-induced forces without failure.

- Structural Adaptation Features:** Incorporates adjustable piers equipped with bearings and flexible connections that allow vertical movement while maintaining structural integrity and load distribution during all phases of operation.

Block Diagram / Flowchart of Methodology

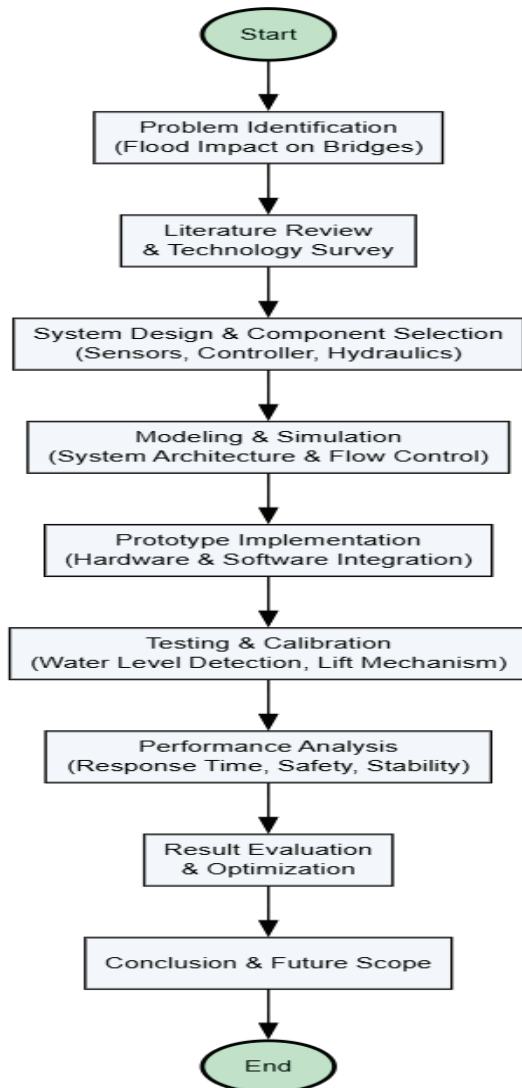


Figure 1: Flowchart of Methodology

- Problem Identification:** Recognizing the need for a flood-responsive bridge system to ensure continuous transport safety.
- Literature Review:** Studying existing hydraulic systems, automation techniques, and related flood-safety mechanisms.
- Design & Simulation:** Developing the bridge's architecture using sensors, controllers, and hydraulic actuators in a simulated environment.

- Implementation & Testing:** Building a prototype and testing its performance under variable water-level conditions.
- Analysis & Conclusion:** Evaluating system efficiency, optimizing control logic, and summarizing results for future improvements.

DESIGN AND DEVELOPMENT

Microcontroller Arduino/ESP32

The ESP32 is a powerful and versatile microcontroller developed by Espressif Systems, designed for low-power IoT (Internet of Things), embedded, and automation applications.

Table 1: ESP32 Controller – Properties and Specifications

Category	Specification
Microcontroller	Tensilica Xtensa LX6 (dual-core or single-core)
Clock Speed	Up to 240 MHz
Operating Voltage	2.2V to 3.6V (typically 3.3V)
Flash Memory	4 MB (varies with module)
SRAM	520 KB
External Storage	Supports SPI flash and SD card
Wi-Fi	802.11 b/g/n (2.4 GHz), up to 150 Mbps
Bluetooth	v4.2 BR/EDR and BLE (Bluetooth Low Energy)
GPIO Pins	Up to 34 programmable GPIOs
ADC (Analog to Digital Converter)	12-bit SAR ADC with up to 18 channels
DAC (Digital to Analog Converter)	8-bit DAC, 2 channels
PWM Channels	Up to 16 channels
Communication Interfaces	SPI, I2C, I2S, UART, CAN, IR, SDIO
Timers	4 × 64-bit timers
Touch Sensors	Up to 10 capacitive touch GPIOs
Temperature Sensor	Integrated onboard sensor
Operating	-40°C to +125°C

Temperature	
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A DC (Direct Current) motor is an electromechanical device that converts electrical energy into mechanical rotational motion. It operates on the principle that a current-carrying conductor placed in a magnetic field experiences a force proportional to the current and magnetic field strength. The ESP32 or motor driver supplies variable voltage or PWM (Pulse Width Modulation) signals to control the motor's speed and direction.

Table 2: DC Motor – Specifications

Parameter	Specification
Type	Brushed DC Motor
Operating Voltage	6V – 12V DC
No-Load Speed	100 – 300 RPM (depending on model)
Rated Current	60 – 250 mA
Stall Current	700 – 1200 mA
Torque	0.5 – 2.5 kg·cm
Direction Control	Bidirectional (using H-bridge or motor driver)
Control Method	PWM (Pulse Width Modulation)
Shaft Diameter	6 mm (typical)
Applications	Robotics, automation, conveyor systems, mobile robots

DC motors are widely used in robotic and automation applications due to their simplicity, compactness, and ease of control. In this project, the DC motor is used to provide mobility to the robot by driving the wheels, enabling forward, backward, and turning movements depending on the control logic from the microcontroller.

Connecting Wires

Connecting wires play a crucial role in establishing reliable electrical connections between various components in an electronic system. They are used to transmit power and signals from the microcontroller to the actuators, sensors, and drivers. Typically made of copper and insulated with PVC or silicon, these wires ensure minimal resistance and signal loss.

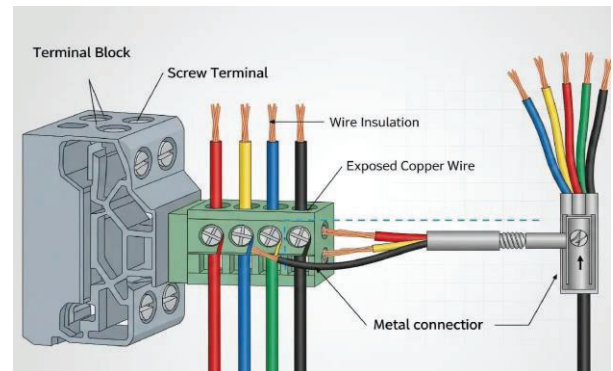


Figure 2: Connecting Wires

The choice of wire gauge depends on the current-carrying requirement of the circuit. In this project, male-to-female and male-to-male jumper wires are used on a breadboard and PCB setup to connect components like the ESP32, L293D motor driver, ultrasonic sensor, and power supply.

Table 3: Connecting Wires – Specifications

Parameter	Specification
Conductor Material	Pure Copper
Insulation Material	PVC or Silicone Rubber
Wire Type	Male-to-Male, Male-to-Female, Female-to-Female Jumper Wires
Wire Gauge (AWG)	22 – 26 AWG
Voltage Rating	Up to 300V
Current Carrying Capacity	Up to 1A
Temperature Range	-20°C to +80°C
Typical Length	10 cm to 30 cm
Color Coding	Multi-colored for easy identification
Applications	Breadboard, PCB connections, prototyping, and circuit interfacing

Motor Driver(L293D)

The L293D motor driver IC is a bidirectional motor control device that allows low-current control signals from a microcontroller to drive high-current DC motors. It operates as an H-bridge, enabling the control of both the direction and speed of two DC motors independently. The L293D can handle output currents up to 600 mA per channel and operating voltages up to 36V. It includes internal diodes for back-EMF protection, ensuring safety

for connected components like the ESP32. In this project, the L293D motor driver acts as an interface between the ESP32 and the motors, amplifying control signals and enabling precise robotic motion control.

Table 4: Motor Driver (L293D) – Specifications

Parameter	Specification
IC Type	Dual H-Bridge Motor Driver IC
Operating Voltage	4.5V – 36V DC
Logic Input Voltage	5V TTL compatible
Output Current (per channel)	600 mA continuous
Peak Output Current	1.2A per channel
Number of Channels	2 (can drive two DC motors)
Enable Control	Separate enable pins for each channel
Protection	Internal ESD protection and back-EMF diodes
Power Dissipation	1W at 75°C (typical)
Package Type	16-pin DIP
Applications	DC motor control, robotic motion control, automation systems

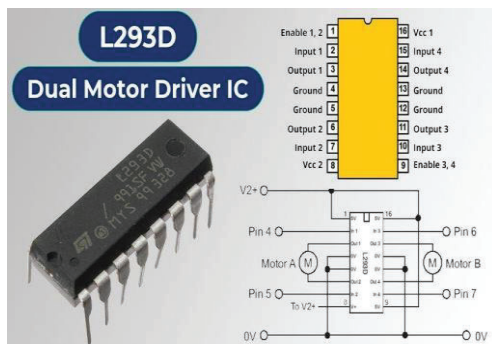


Figure 3: Motor Driver (L293D)

Power Supply

The power supply unit provides the required electrical energy for the operation of the ESP32, sensors, and actuators. It converts AC mains or DC input into a stable regulated voltage suitable for each component.

Typically, a 5V regulated supply is used for the ESP32 and motor driver, while the motors may operate at 6V–12V, depending on the load. Battery packs or adapter-based supplies can be employed to ensure uninterrupted performance. The stability of the power supply is crucial

to prevent voltage fluctuations that may cause malfunctioning of sensors or microcontrollers during operation.



Figure 4: Power Supply

Table 5: Power Supply – Specifications

Parameter	Specification
Input Voltage	100 – 240V AC, 50/60 Hz
Output Voltage	5V DC (for logic), 9V–12V DC (for motors)
Output Current	1A – 2A (depending on load)
Regulation	±5%
Connector Type	Barrel jack or screw terminal
Protection Features	Over-voltage, short-circuit, and thermal protection
Power Source Type	Adapter or rechargeable battery pack
Efficiency	> 80%
Operating Temperature	0°C to +70°C
Applications	Powering ESP32, motor driver, and sensors in robotics projects

Ultrasonic Sensor

Table 6: Ultrasonic Sensor (HC-SR04) – Specifications

Parameter	Specification
Model	HC-SR04
Operating Voltage	5V DC
Operating Current	15 mA

Sensing Range	2 cm – 400 cm
Accuracy	±3 mm
Measuring Angle	≤ 15°
Trigger Input Signal	10 μs TTL pulse
Echo Output Signal	TTL signal, proportional to distance
Operating Frequency	40 kHz
Response Time	< 50 ms
Dimensions	45 mm × 20 mm × 15 mm
Applications	Obstacle detection, distance measurement, navigation systems



Figure 5: Acrylic Material

Acrylic Material

Acrylic material (Polymethyl Methacrylate – PMMA) is a transparent, lightweight, and durable thermoplastic often used as a structural component in robotics and electronic enclosures. It is easy to cut, drill, and shape, making it ideal for fabricating the robot’s chassis or housing. Acrylic offers high impact resistance and excellent optical clarity, making it both functional and visually appealing.

In this project, acrylic sheets are used to design the robot’s body and mounting frame for sensors, motors, and the controller board, providing both mechanical support and aesthetic design.

Table 7: Acrylic Material – Specifications

Parameter	Specification
Material Name	Polymethyl Methacrylate (PMMA)
Common Name	Acrylic Sheet / Plexiglass
Density	1.18 g/cm ³
Thickness Range	2 mm – 10 mm (project-specific: 3 mm typical)
Transparency	92% light transmission
Hardness	Rockwell M95
Tensile Strength	65 MPa
Flexural Strength	90 MPa
Melting Point	160°C
Water Absorption	< 0.4%

CONCLUSION

This research successfully demonstrated the feasibility and effectiveness of a hydraulic adjustable bridge system that autonomously responds to fluctuating river water levels. The system integrates advanced sensor technologies, a reliable hydraulic actuation mechanism, and a smart control unit to dynamically elevate the bridge deck, thereby ensuring uninterrupted transportation during flood events. Performance evaluations highlighted rapid response times, precise elevation control, and robust structural stability under simulated flood scenarios. Comparative analysis with conventional fixed bridges underscored significant improvements in flood resilience, safety, and operational continuity. The materials and equipment selected provide optimized durability, corrosion resistance, and adaptability to extreme environmental conditions.

The study concludes that hydraulic adjustable bridges offer a transformative advancement in flood-resistant infrastructure. By actively adapting bridge elevation in real-time, the system mitigates common flood-related risks such as submersion, scour, and debris impact, which traditionally compromise bridge structural integrity and accessibility.

Although the design introduces added complexity and dependence on power and control systems, these trade-offs are outweighed by the system’s ability to significantly reduce flood damage, enhance public safety, and maintain critical transport links during adverse weather. This technology aligns closely with global climate adaptation strategies, providing a resilient, intelligent solution to infrastructure challenges posed by increasing flood events.

Future Scope and Improvements

Opportunities for further research and system enhancement include

- **Energy Optimization:** Incorporating renewable energy sources such as solar or wind to power hydraulic pumps, reducing operating costs and enhancing sustainability.
- **Advanced Sensing and IoT Connectivity:** Expanding sensor arrays with IoT-based realtime monitoring networks and predictive analytics to improve early flood detection and system responsiveness.
- **Multi-Span and Large-Scale Application:** Extending adaptive elevation designs to multi-span or longer

bridges with coordinated hydraulic actuation and load balancing.

- **Alternative Actuation Technologies:** Exploring pneumatic, electro-mechanical, or smart material-based actuation to reduce maintenance and increase flexibility.
- **AI-Driven Control Algorithms:** Leveraging machine learning to optimize system responsiveness and fault detection under complex flood dynamics.
- **Integration with Urban Infrastructure:** Embedding the system into smart city frameworks for holistic flood risk management and transportation network resilience.
- **Long-Term Field Testing:** Conducting extended operational trials in diverse flood-prone geographical settings for validation and refinement

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