Proceedings of the 21st ICSMGE, Vienna, Austria, 14 – 19 June 2026. Pistrol, Adam & Schweiger (eds.)
Published by: ÖGG, Austrian Society for Geomechanics, Salzburg, Austria, ISBN 978-3-9503898-4-5
https://doi.org/10.53243/ICSMGE2026-2369

Evaluation of bridge damage risk during heavy rainfall considering driftwood generation from slope failures and riverside forests

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ABSTRACT: In recent years, intensified and concentrated rainfall has increasingly caused geo hazards and bridge damage due to rising river discharge. A major concern is the accumulation of driftwood around bridges, which blocks river channels and leads to flooding or erosion behind the structures. To ensure efficient bridge maintenance, it is essential to identify high-risk bridges by estimating the volume of driftwood they may capture. However, the current understanding of driftwood generation and transport processes remains limited. This study aims to improve bridge disaster risk assessment by integrating driftwood capture volume and river cross-sectional blockage rate into existing evaluation models. Using machine learning and past disaster records, it estimates landslide risk, driftwood generation potential, and driftwood capture volume for each bridge. A key challenge is that driftwood is not only captured by bridges but also by river bars, which are often covered by riverside forests - additional sources of driftwood not fully reflected in conventional models. To overcome this, the study uses satellite imagery and deep learning to identify driftwood sources from landslides and riverside forests. The volume of generated driftwood is estimated by multiplying the source area by the driftwood outflow rate. Capture volume at each bridge is then calculated, accounting for deposition in riverside zones and bare land. These results are compared with field survey data to validate the model, demonstrating improved accuracy in assessing bridge disaster risk.

KEYWORDS: Driftwood disaster, AI, Risk assessment.

1 INTRODUCTION

In recent years, landslides and slope failures triggered by intense and localized rainfall have become increasingly frequent, along with bridge damage due to rising river flows. Incidents where driftwood becomes trapped at bridges, obstructing river channels and causing flooding or erosion of the ground behind bridge structures, have been repeatedly observed. To ensure efficient maintenance of bridges under such conditions, it is essential to identify and prioritize those at higher risk of damage for the countermeasure. However, research on the processes of driftwood generation, transport, and the mechanism behind related disasters remains ongoing. A key challenge is to establish a rational and efficient method for estimating the volume of driftwood likely to be captured by each river-crossing bridge (Ministry of Land, Infrastructure, Transport and Tourism, Water Management and Land Conservation Bureau, Sabo Department, 2023).

In response to the above challenges, this study estimates the potential for driftwood generation, and the volume of driftwood captured at each bridge by utilizing a machine learning-based landslide risk prediction model trained on past disaster records. Building upon a previously proposed bridge disaster risk assessment method, we enhanced the model by incorporating driftwood capture volume and river cross-section obstruction rate as new factors, aiming to improve its predictive accuracy (Ando et al., 2024). However, in practice, driftwood is not only trapped at bridges but also accumulates on sandbars within river channels. Moreover, riverside forests growing on these sandbars often serve as sources of driftwood, making it difficult to fully capture the complexity of the real phenomena.

To address this, we employed pre- and post-disaster satellite imagery and deep learning techniques to identify driftwood sources originating from slope failures and riverside forests. The volume of driftwood generated (m^3) was calculated by multiplying the area of each identified source (km^2) by a corresponding driftwood runoff coefficient (m^3/km^2). Considering the capture and accumulation of driftwood in riverside forests and bare land, we then estimated the volume of driftwood captured by each bridge within the watershed. The validity of these estimates was assessed through comparison with field survey results.

2 STUDY AREA

The study focuses on the Tokachi river basin in Hokkaido of Japan, targeting 495 national and prefectural road bridges within the basin for disaster risk assessment, including 16 bridges that were damaged during the heavy rainfall event in Hokkaido in August 2016 (Figure 1). Field surveys were conducted along the Tottabetsu river by Kudo et al. (2021) and Memuro river by Ministry of Land, Infrastructure, Transport and Tourism Hokkaido Regional Development Bureau (2024), both located within the Tokachi river basin. The estimated volumes of driftwood generation and capture in these rivers will be compared and analyzed.

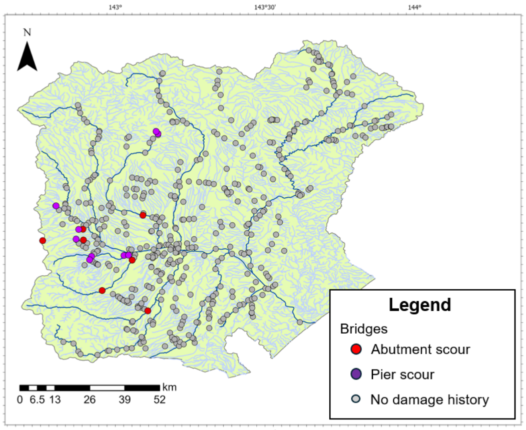

Figure 1. Location of target bridges and record of past damage in Tokachi river basin of Hokkaido (Ando et al., 2024).

3 ANALYSIS METHOD

3.1 *Identification of Driftwood Sources*

In this study, satellite images captured before and after August 2016 heavy rains in Hokkaido - specifically, Landsat imagery from July 7, 2016, and Sentinel imagery from July 14, 2017 (see Figures 2 and 3) - were analyzed using a convolutional neural network (CNN). Vegetation presence was binarized by classifying the images into vegetated and non-vegetated areas. By comparing the vegetation status before and after the rainfall, we identified driftwood sources resulting from slope failures and riverside forests. The identified driftwood sources for the Tottabetsu and Memuro river basins are presented in Figures 4 through 7.

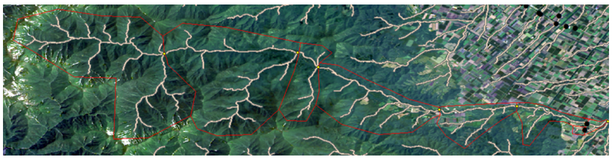
Figure 2. Tottabetsu river basin.


Figure 3. Memuro river basin.


Figure 4. Driftwood sources from slope failures in the Tottabetsu river basin (yellow points).

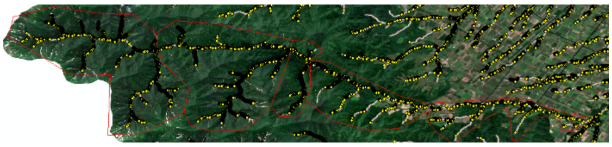
Figure 5. Driftwood sources originating from riverside forests in the Tottabetsu river basin (yellow points).

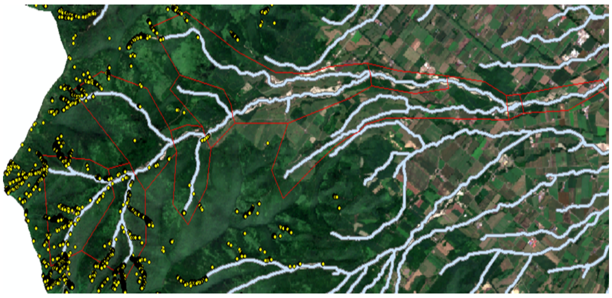
Figure 6. Source of driftwood from slope failures in the Memuro river basin (yellow points).

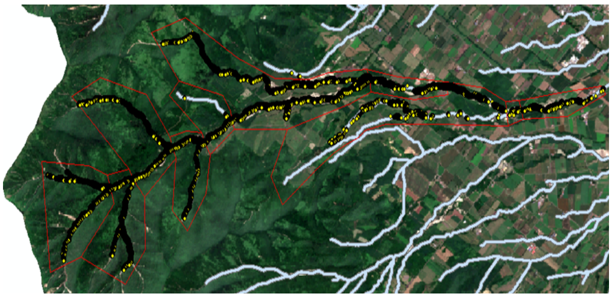
Figure 7. Driftwood sources originating from riverside forests in the Memuro river basin (yellow points).

3.2 *Calculating the volume of driftwood generated*

Next, the volume of driftwood generated was estimated by applying Equation (1), based on Yano et al. (2016), which multiplies the area of the identified driftwood source by the driftwood runoff rate.

$$V_i = \sum_k \beta_k A_{ki} \tag{1}$$

Here, V_i represents the volume of driftwood generated within the catchment area upstream of point i (km³), β_k is the driftwood runoff rate - the volume of driftwood discharged per unit area for each tree species k in the forest (m³/km²), and A_{ki} is the area of driftwood sources within the catchment area upstream of point i (km²).

Following Takemura et al. (2019), β_k was set to 68,680 for conifers in the Tottabetsu river basin and 22,380 for conifers in the Memuro river basin, based on the dominant tree species' ages in each basin. Additionally, based on previous research (Yano et al., 2016), the driftwood runoff rate for broadleaf trees in both basins was assumed to be one-tenth that of conifers. Vegetation distribution within the watershed was derived from a vegetation survey conducted by the Ministry of the Environment's Natural Environment Bureau at a 1:25,000 scale (Ministry of the Environment, Natural Environment Bureau, 2022).

Driftwood resulting from slope failures was considered to have entered the river channel if it met the conditions defined by Moriwaki's empirical formula (Moriwaki, 1987), as shown in Figure 8 and Equation (2). Additionally, it was assumed that all driftwood generated in riverside forests flows directly into the river.

$$H / L_{max} = 0.73 tan\theta - 0.21 \tag{2}$$

Here, L_{max} denotes the maximum reach distance, θ is the slope angle (where $\tan\theta = H' / L'$), H is the elevation difference from the river, and L_r is the horizontal distance from the driftwood source to the river inflow point corresponding to that source. The value of L_r was calculated as the shortest path from the slope to the river channel without crossing any ridges, based on the method described by Yano et al. (2016).

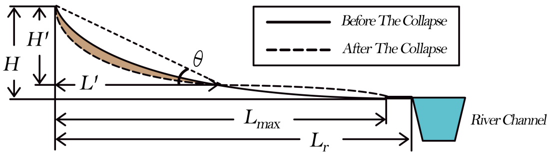

Figure 8. Calculation method for distance traveled by collapsed soil due to slope failure (Moriwaki 1987; Yano et al., 2016).

The calculation results for the Tottabetsu river basin are presented in Figures 9 to 11, while those for the Memuro river basin are shown in Figure 12. These results are compared with findings from Kudo et al. (2021) for the Tottabetsu river basin and the materials provided by the Tokachi river basin erosion control technology review committee (Ministry of Land, Infrastructure, Transport and Tourism Hokkaido Regional Development Bureau, 2022) for the Memuro river basin. Since both references divide the basins into 6 and 9 sections respectively, this study also adopted the same sectional divisions for comparison.

From the figures, it was confirmed that driftwood sources can be identified and their volumes estimated using satellite imagery combined with deep learning-based image classification, although some quantitative discrepancies remain. Since this study applied a uniform driftwood runoff rate based on the dominant tree species in each watershed, a more detailed specification of driftwood runoff rates will be required to enhance the accuracy of driftwood volume estimation. However, the observed trend in the Tottabetsu river - where driftwood from riverside forests is more dominant than that from slope failures - was successfully captured, underscoring the importance of accurately estimating driftwood originating from riverside forests.

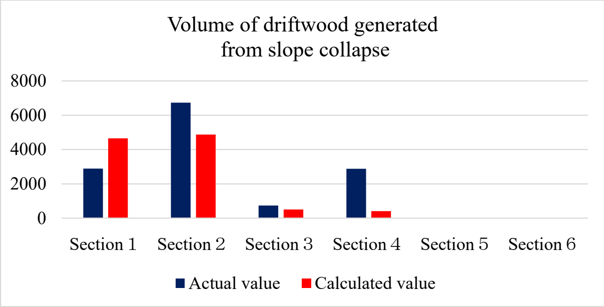

Figure 9. Volume of driftwood generated by slope failures in the Tottabetsu river basin.

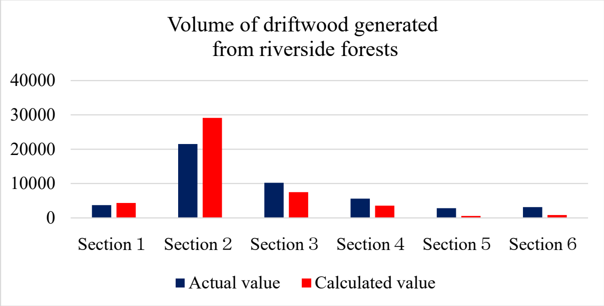

Figure 10. Volume of driftwood generated from riverside forests in the Tottabetsu river basin (m^3).

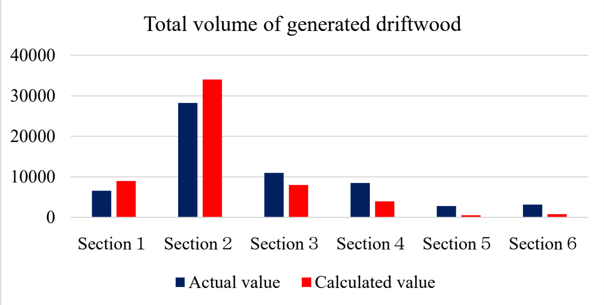

Figure 11. Comparison of total volume of driftwood generated in the Tottabetsu river basin (m^3).

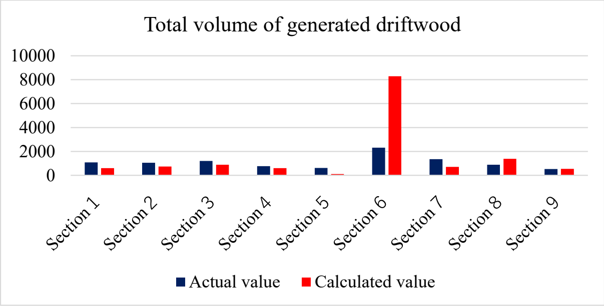

Figure 12. Comparison of total volume of driftwood generated in the Memuro river basin (m^3).

3.3 *Calculating the volume of driftwood captured*

Following Akahori et al. (2008), the capture rates for driftwood in riverside forests and bare land within the river channel were set at 6.85% and 0.2%, respectively. The volume of driftwood captured in these areas was then calculated by multiplying these rates by the driftwood volume generated in each section, as determined earlier. Meanwhile, based on Akiyama et al. (2021) and Sakio and Matsuzawa (2016), the maximum driftwood capture capacity was defined according to the area of the riverside forest and bare land. If the initially calculated captured driftwood volume was below this maximum capacity, that value was adopted; if it exceeded the capacity, the maximum capacity was used as the captured volume for the section. Finally, the volume of driftwood captured at each bridge was calculated using the driftwood capture rate definition outlined in previous studies (Ando et al., 2024) as shown below.

$$v_i = (V_i - v_{i-1} - \cdots v_2 - v_1) \times \alpha_i = \alpha_i \left(V_i - \sum_{k=1}^{i-1} v_k\right) \qquad (3)$$

Here, V_i represents the volume of driftwood generated in the upstream area of the i-th bridge (m^3), v_k is the volume of driftwood captured by the k-th bridge located upstream of the i-th bridge (m^3), and α_i denotes the driftwood capture rate determined by the structure of the i-th bridge. The capture rate α_i, which reflects the bridge's effectiveness in trapping driftwood, is primarily influenced by the driftwood length and the channel width during floods and is thus defined by Equation (4) below (Yano et al., 2016).

$$\alpha_i = \frac{L_w}{W_i} \times \frac{1}{\gamma} \qquad (4)$$

Here, L_w is the average driftwood length in the target watershed (m), W_i is the minimum channel width at the i-th bridge during high water levels (m), and γ is a coefficient representing the difficulty of driftwood accumulation at the bridge.

The average tree length was estimated by calculating the difference between the DSM (Digital Surface Model) data - which includes surface elevations of trees and buildings - and the DEM (Digital Elevation Model) data for the Tottabetsu and Memuro river basins. The average driftwood length L_w was then derived from the ratio of driftwood volumes generated by slope failures to those from riverside forests and divided by two, resulting in 3.96 m for the Tottabetsu river basin and 2.80 m for the Memuro river basin. The minimum channel width W_i at each bridge during high water was obtained from general bridge design diagrams for each bridge. Although the coefficient γ carries some uncertainty, this study adopted a value of 3.70 based on Shimizu et al. (2018).

Figures 13 and 14 show the estimated driftwood capture volumes for the Tottabetsu and Memuro river basins, respectively. When comparing these calculated capture volumes to actual field measurements, the method provided more accurate estimates than conventional approaches (Ando et al., 2024) that only consider driftwood captured directly at bridges. However, since the capture rate in this study was derived from limited data, the estimation accuracy of driftwood capture was lower than that for driftwood generation, and some sections exhibited significant errors. Future improvements should focus on incorporating more detailed factors affecting driftwood capture, such as riverbed slope and the species and density of riverside forests, to enhance prediction accuracy.

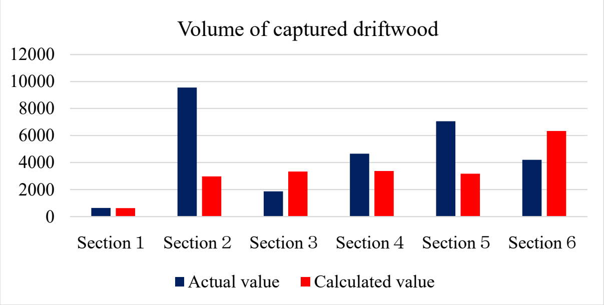

Figure 13. Comparison of total volume of driftwood captured in the Tottabetsu river basin (m^3).

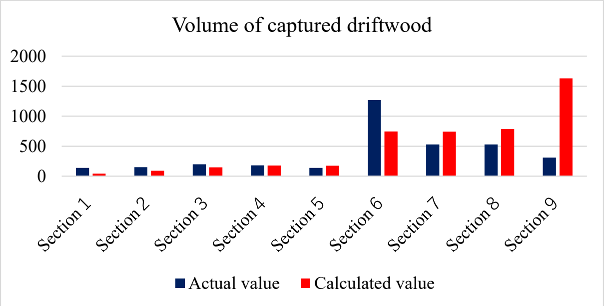

Figure 14. Comparison of total volume of driftwood captured in the Memuro river basin (m^3).

4 RISK ASSESSMENT OF BRIDGE DAMAGE DURING HEAVY RAIN

Finally, a bridge damage risk assessment was performed using machine learning for bridges with both single and multiple spans in the Tokachi river basin. This assessment utilized 11 types of predisposing factors at each bridge location, including river width, river channel plan curvature, catchment area, riverbed gradient, the angle between the bridge and river channel, surface geology, bridge age, bridge length, number of spans, volume of driftwood captured, river crossing obstruction rate, and damage history. Figure 15 presents the damage risk assessment results obtained using a random forest model, which demonstrated the highest accuracy. The figure shows that while many bridges with relatively high risk are in the northwest part of the basin, there are also bridges in the northeast exhibiting characteristics similar to those damaged during the August 2016 Hokkaido heavy rains, despite having not suffered damage themselves.

Further examination of the disaster cases revealed that single-span bridges primarily experienced erosion damage behind abutments, whereas multi-span bridges were more prone to scouring damage around the bridge foundations. The analysis also indicated that the significance of each risk factor varies between single-span and multi-span bridges: the volume of trapped driftwood plays a particularly large role in single-span bridge damage, while both the volume of trapped driftwood and the river area obstruction rate are important contributors for multi-span bridges. These findings align well with the observed characteristics of the disaster cases.

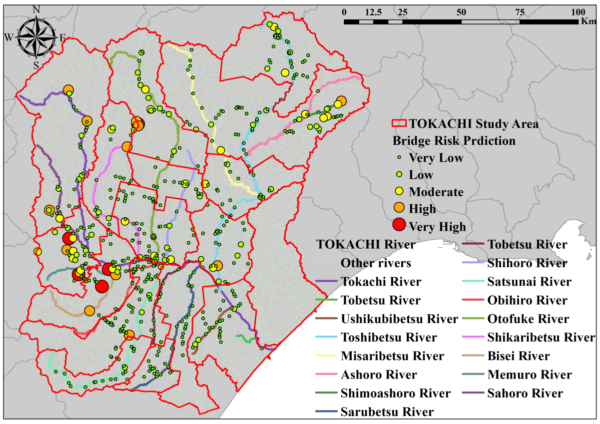

Figure 15. Risk assessment of bridge damage during heavy rains in the Tokachi river basin of Hokkaido.

5 CONCLUSIONS

Using satellite images and deep learning to identify driftwood sources originating from slope failures and riverside forests and estimating the volume of driftwood captured at each bridge, we improved the accuracy of existing bridge disaster risk assessment models by considering the cross-section obstruction rate. Furthermore, it is clearly demonstrated that the volume of trapped driftwood plays a particularly large role in single-span bridge damage, while both the volume of trapped driftwood and the river area obstruction rate are important contributors for multi-span bridges.

6 ACKNOWLEDGEMENTS

This research was supported by JSPS KAKENHI Grants 23K04019 and 24K00985. I would like to express our sincere gratitude here.

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