THE EFFECTIVENESS OF FLOOD DEFENSE FORESTS AS THE FLOOD CONTROL IN THE LOWER REACH OF GOUNOKAWA RIVER

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ABSTRACT

The Gounokawa River has the maximum basin area in the Chugoku region, with its lower reaches located in the Shimane Prefecture in Japan. In the lower reaches of the Gounokawa River, many districts without dikes exist, and the degree of river improvement security is low. In addition, it is expected that the local population will decrease by more than 30% in the next 30 years. Therefore, it is difficult to construct dikes with a degree of progress similar to that in the past. However, bamboo trees planted as flood reduction measures still remain as flood defense forests. Therefore, in the lower reaches of the Gounokawa River, it is important to utilize the flood defense forests for river security improvement. Flood water depths are high, and early velocity acts on the flood defense forests, which may be lodged and washed away. However, these risks have not been considered for large-scale flooding. In this study, we built a numerical analysis model (2-D shallow-water flow model) capable of quantitatively calculating river improvement effects and lodging of flood defense forests. We evaluated the lodging of flood defense forests based on the bending moment acting on them at the time of flooding. We performed a quantitative evaluation of the river improvement effect of the flood defense forests in the lower reaches of the Gounokawa River and examined the maintenance policy utilized for river improvement effects. In addition, based on our assumptions about lodging flood defense forests at the time of large-scale flooding, we considered differences due to floodplain velocity.

Keywords: Flood defense forests, Flooding water, Flood control effectiveness, Lodging flood defense forests, Velocity of floodplain

1   INTRODUCTION
1.1 Flood defense forest

Flood defense forests are bamboo forests planted to alleviate flood damage before a dike is built; they reduce flood flow velocity and control bank erosion. However, over the recent years, flood defense forests have been cut down to expand river widths and increase embankments throughout Japan. In response to the growing interest in the environment, river environment preservation, as well as flood control, is becoming important, and the original function of the flood defense forest is beginning to be reconsidered.

In addition to the Gounokawa River, other flood defense forests were planted along the Yoshino River (Tokushima Pref.), the Adogawa River (Shiga Pref.), and the Yuragawa River (Kyoto Pref.) They still exist throughout Japan and have long been maintained in anticipation of their flood controlling effects. Therefore, many studies have investigated flood defense forests and their flood control effects. It is a bamboo forest with a width of 30 m or more as a feature of flood defense forests which showed its effect at the time of large flood, it has been growing over a long range in the longitudinal direction and that the number of bamboo per 100 m^2 is 600 to 900 (Yoshino, 1978).

Bamboo forests that were planted as measures against flood damage as per the teachings of "Kobo Daishi" in the lower reaches of the Gounokawa River still remain. However, in recent years, due to the withering of flood defense forests and expansion of the extent of proliferation, the water level rises during floods. Therefore, in the lower reaches of the Gounokawa River, it has become important to utilize the flood defense forest for river improvement.

1.2 Bamboo material properties

Currently, many bamboo groves in Japan are being neglected, which has led to their general devastation. At the same time, experiments to grasp the fundamental material properties of bamboo are being carried out to utilize bamboo as a building structure. Yoshida et al have tested bending, compression shearing, tension and splitting using Mousou bamboo growing near Yokohama City. In the full-scale experiment, using unmodified bamboo test bodies, the bending stress, σ_b, was 6.1 to 7.7 kN/cm^2. In addition, these values were compared with experimental data from other laboratories. However, because the results shown in Table 1 differ in the location of specimen extraction and specimen shape, the data varies. In this study, the bending

stress σ_b from the bamboo material property test result is used as the threshold for judging lodging; the validity is examined by comparing the experimental results with the flood result from July, 1983.

Table 1. Bamboo bending test results

Testing institution		Bending stress (kN/cm^2)
Tokyo Univ.		12.2
Oita Univ		14.4
Washington State Univ.		10.5
Univ. Aachen		7.6
Polytechnic Univ.	Test piece experiment	19.0
	Full-scale experiment	6.1

2   Study Methods

2.1   The target area

The Gounokawa River has a maximum basin area in the Chugoku region, with the lower reaches located in Shimane Prefecture in Japan. This research targeted the Tazu district, an area with few dikes located on the left bank, approximately 21 to 23 km from the estuary. On the riverbank, there is a 90 m wide Mousouchiku flood defense forest, wherein the bamboos reach heights of approximately 15 m, a breast height diameter of 70 mm, and a density of 3 to 8 threads/m^2. On the right bank of Tazu district lies Onuki district, which is currently developing interim dikes. The flood defense forest in Tazu district both hinders flood flow and is a factor in rising upstream water levels. Therefore, from the viewpoint of the flood control plan, it is necessary to cut down the flood defense forest, but it is important to utilize the flood protection forest because the dikes are undeveloped.
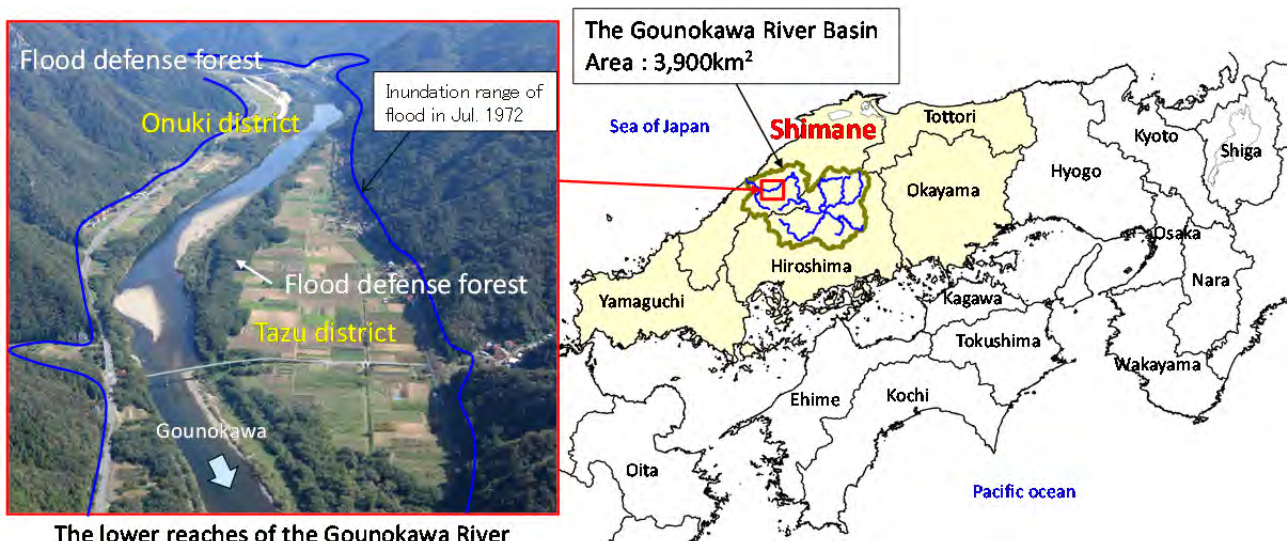
Figure 1. Position map of the lower reaches of the Gounokawa River

2.2   Outline of the numerical analysis model

In order to evaluate the flood effect of the flood defense forest and to examine management of the flood defense forest, a 2-D shallow-water flow model was created.

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial s} + v\frac{\partial u}{\partial n} + \frac{uv}{r} \quad\quad\quad [1]$$
$$= -g\frac{\partial H}{\partial s} - \frac{\tau_s}{\rho h} + 2\frac{\partial}{\partial s}\left[\varepsilon\frac{\partial u}{\partial s}\right] + \frac{\partial}{\partial n}\left[\varepsilon\frac{\partial u}{\partial n}\right]$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial s} + v\frac{\partial v}{\partial n} - \frac{u^2}{r} \qu\quad\quad\quad [2]$$
$$= -g\frac{\partial H}{\partial n} - \frac{\tau_n}{\rho h} + \frac{\partial}{\partial s}\left[\varepsilon\frac{\partial v}{\partial s}\right] + 2\frac{\partial}{\partial n}\left[\varepsilon\frac{\partial v}{\partial n}\right]$$

$$\frac{\partial H}{\partial t} + \frac{\partial(uh)}{\partial s} + \frac{\partial(vh)}{\partial n} + \frac{vh}{r} = 0 \quad\quad\quad [3]$$

where, u is water depth average flow velocity in the s direction, v is water depth average flow velocity in the n direction, r is the curvature radius of the flow channel, g is gravitational acceleration, H is water level, h is water depth, ρ is fluid density, and t is time. τ_s, τ_n are the riverbed shear stress in the s and n directions and are given in Eq. [4] and [5]. And n is the coefficient of roughness.

$$\frac{\tau_s}{\rho h} = \frac{gn^2}{h^{4/3}} u\sqrt{u^2 + v^2} \qquad\qquad [4]$$

$$\frac{\tau_n}{\rho h} = \frac{gn^2}{h^{4/3}} v\sqrt{u^2 + v^2} \qquad\qquad [5]$$

The coefficient of eddy viscosity ε, is provided assuming logarithmic law in the water depth direction as shown in Eq. [6].

$$\varepsilon = \frac{\kappa}{6} u_* h \qquad\qquad [6]$$

where, κ is the Karman constant, and u_* is the friction velocity.

2.3 The vegetation model

The vegetation model is treated as Eq. [7] and [8], assuming an equivalent roughness coefficient calculated from the characteristics of tree growth (diameter, denseness etc.). The vegetation transmission coefficient K, representing the tree propagation characteristic is expressed by Eq. [7].

$$K = (2 \cdot g / a_w / C_d)^{0.5} \qquad\qquad [7]$$

where, $a_w = N*D_m$, the drag coefficient $C_d = 1.2$, and g is gravitational acceleration. n is the number of trees growing per unit area, and D_m is breast high diameter.

The roughness coefficient, considering the growth of the vegetation, is represented by Eq. [8] according to water depth.

$$
\begin{array}{ll}
h_m = 0 & n = \infty \\
h_m > 0 \text{ and } h \le h_m & n = \left(n_b^2 + h^{4/3}/K^2\right)^{0.5} \\
h_m > 0 \text{ and } h_m < h \le h_v & n = (h/h_m)^{5/3} \cdot \left(n_b^2 + h_m^{4/3}/K^2\right)^{0.5} \\
h_m > 0 \text{ and } h_v < h & n = (h_v/h_m)^{5/3} \cdot \left(n_b^2 + h_m^{4/3}/K^2\right)^{0.5}
\end{array} \qquad [8]
$$

where, h_m is the branch length, h_v is tree height, and n_b is the roughness coefficient of the surface of the high-water site within the range of tree group growth.

2.4 Confirmation of hydraulic analysis model reproducibility

We confirmed the validity of the hydrological analysis model for the flood in Jul, 2010, which was the largest flood in recent years (Kawahira St.: 5,817 m^3/s).

Figure 2 shows the flood mark at 20 km to 30 km, the target section of this study, and the observed water level in the Tanijugo water gauge station (right bank 14.8 km), in the vicinity of the target section. The average water level difference from the flood mark was 0.28 m, and the difference from peak water level at the observation station was 0.11 m. This confirmed that the flood can be reproduced on both the water surface shape and hydrograph.
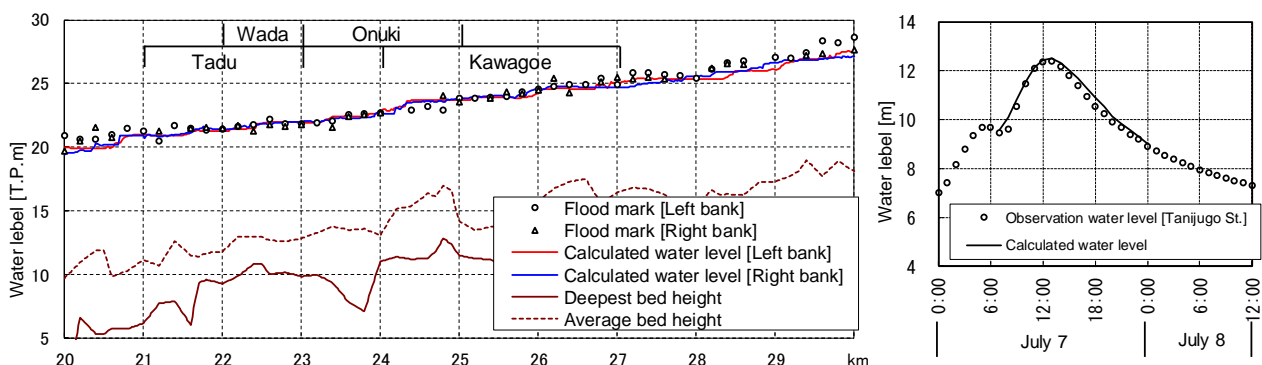

**Figure 2**. Flood mark longitudinal section and water level hydrograph

3   The management method for flood defense forests

3.1 Case setting

In order to examine the management method for flood defense forests, the following cases were set and the optimum management method was selected.

Table 2. Case settings for flood defense forest management

	State of flood defense forest	
	The down stream side	The up stream side
Case1	Remove	Remove
Case2	Leave	Remove
Case3	Remove	Leave
Case4	Leave at 20 m width	Leave at 20 m width
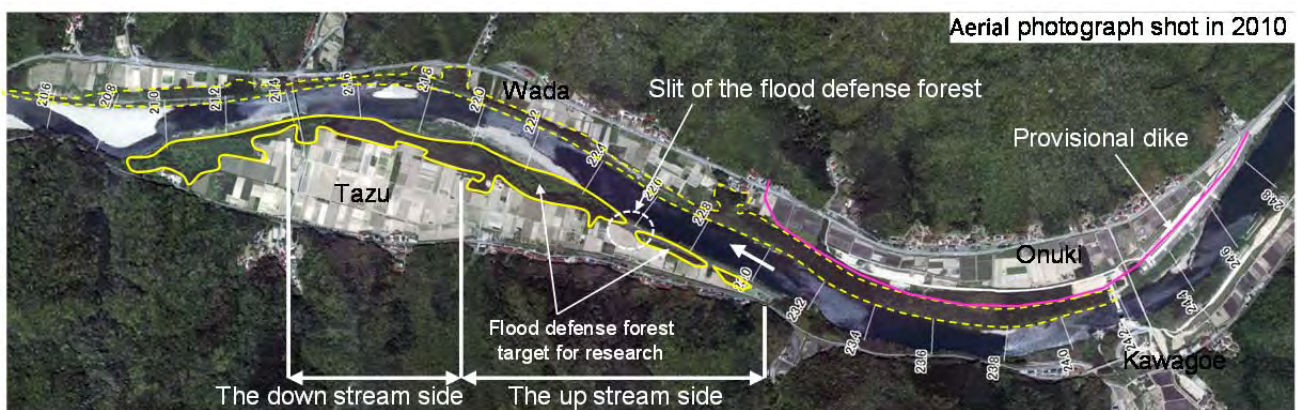
Figure 3. Position map of flood defense forest in the Tazu district

3.2 Numerical analysis results

Figure 4 shows the maximum flow velocity plan view for the flood in July, 1972; Figure 5 shows the maximum flow velocity plan view for the flood in July, 1983. The flood in July, 1972 had a large-scale water discharge (Gotsu St.: 10,400 m^3/s), while the flood in July, 1983 was a mid-scale water discharge (Gotsu St.: 7,800 m^3/s).

3.2.1   The Tazu district (Left bank 21 km to 23 km)

An overflowing flood occurred in the Tazu district because the dike was not well developed. In Case 1, because the flood defense forest is nonexistent, the mean value of flow velocity inside the flood plain rises to 1.2 m/s, and the effect of reduction in the velocity from the flood defense forest disappears.

In Case 2, the flood flow velocity increases from the upstream side, at the location of flood defense forest lodging, and flows into the inside of the flood plain; the velocity inside the flood plain rises compared with the current river channel. In addition, the flow velocity increases locally, immediately upstream of the flood defense forest outlet. This implies that the flow direction changed toward the inside of the flood plain due to the resistance of the flood defense forest, as the upstream end of the remaining flood defense forest is wide.

In Case 3, the downstream velocity of the flood plain where the flood defense forest was removed is not significantly different compared to the current river channel. However, the flow velocity in the vicinity of the small amount of the flood defense forest on the upstream side increases compared to the current river channel. It is hypothesized that this is due to the flood defense forest lodging on the downstream side, so that the flow on the flood plain is unimpeded downstream and the flow velocity is increased upstream.

In Case 4, the flow velocity in the flood plain remains unchanged compared with the current river channel. By maintaining the flood defense forest with a width of 20 m, it is possible to utilize the flood defense forest to reduce flow velocity.

3.2.2   The Onuki district (Right bank 23 km to 25 km)

Because the flood in July, 1974 was large-scale, overflowing flooding would occur in all cases due to flow capacity even if the provisional dike is constructed. Flooding in July, 1983 was at such a flow rate scale that it would flow below the dike level. Overflow flooding in Cases 1, 3, and 4 is eliminated.
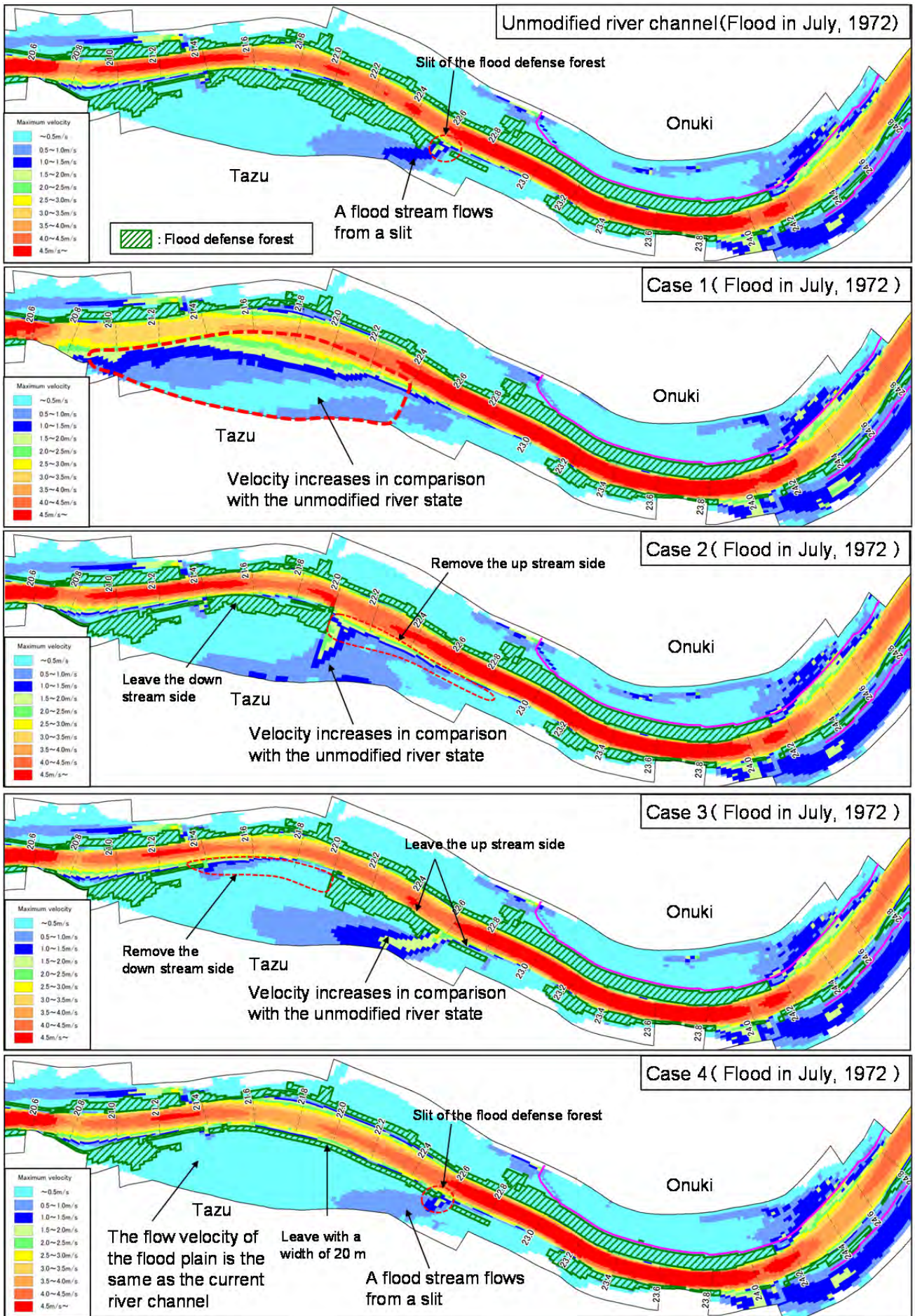
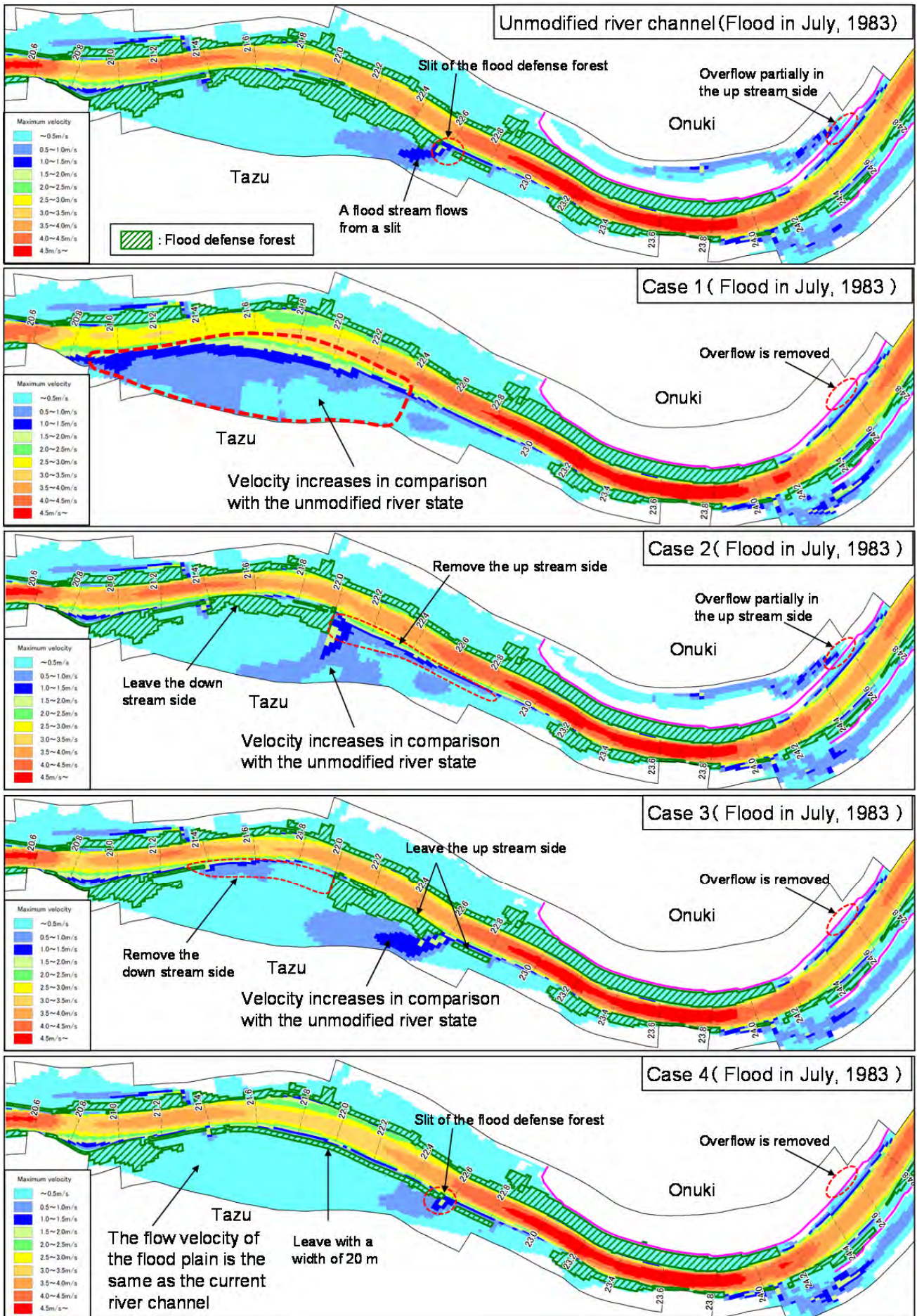**Figure 4**. Velocity distribution map of the flood in July, 1972

Figure 5. Velocity distribution map of the flood in July, 1983

3.3 Optimal management method
The advantages and disadvantages of removing sections of the flood defense forest were comprehensively evaluated and improvement methods for the flood defense forest in the Tazu district were selected. In Table 3, modifications that resulted in improvements compared to current river channels are indicated with ◯ modifications that resulted in neither improvement or worsening are indicated with a △ and modifications that deteriorate the exiting conditions are indicated with an ×. The evaluation results suggest that Case 4, maintaining a flood defense forest with 20 m width, is the best modification of the four cases.

Table 3. Comprehensive evaluation of flood defense forest management methods

	Tazu district		Onuki district		Comprehensive evaluation
	Flood in July, 1972	Flood in July, 1983	Flood in July, 1972	Flood in July, 1983	
Case1	×	×	◯	◯	×
Case2	×	×	△	△	×
Case3	×	×	△	◯	×
Case4	△	△	◯	◯	◯

4   Consideration on lodging situation of flood defense forest

4.1 Consideration lodging from the flood in July, 1987
In this chapter, a 2-D shallow-water flow model was constructed for flood mitigation in July, 1983, where lodging data from the flood protection forest after flooding is available. In order to reproduce the flow condition at the time of the flood in July, 1983, topography data was created using survey results immediately after the flood. The range of the flood defense forest was set from aerial photographs taken in 1987 after the flood. In the target section (20 km to 30 km) of this study, the dike was not developed in all the areas, so it became a unified flow with the floodplain, damages such as house flooding, erosion / sedimentation of flood plains, collapse of protection banks , And the flood defense forest lodged. Fig. 6 shows the aerial photographs after the flooding (shot in 1988) and the lodging situation of the flood defense forest at the flood in July, 1983 (March, 1984 survey).
Based on the model and flooding, the bending stressed acting on flood defense forest was calculated. The bending stress σ_f acting on the flood defense forest and the bending stress σ_b from the bamboo material property test result were compared and the threshold value for lodging was evaluated. The bending stress degree σ_f acting on the flood defense forest is given by Eq. [9].

$$\sigma_f = \frac{M}{W} \qquad\qquad [9]$$

where, M is the external force moment and is given by Eq. [10] using water depth and flow rate obtained from hydraulic analysis. W is the section modulus, obtained from the bamboo diameter as shown in Eq. [11].

$$M = \frac{1}{2}\rho C_D S u^2 L \qquad\qquad [10]$$

where, ρ is water density, C_D is the drag coefficient of the tree, S is the area of action of drag, u is the flow velocity, and L is the length from the center of destruction to the drag center.

$$W = \frac{\pi}{32}\frac{D^4 + d^4}{D} \qquad\qquad [11]$$

where, D is the bamboo diameter, and d is the bamboo thickness.

The degree of bending stress calculated from the hydraulic quantity for each mesh at the retention and lodging points (refer to Figure 6) of the flood defense forest is shown in Figure 7. The bending stress calculated from the average hydraulic quantity is shown in Table 4. In places where the flood defense forest was dislodged during the July, 1983 flood, the bending stress σ_f acting on the flood defense forest is greater than the experimentally derived bending stress σ_b, 6.1 kN/cm^2, of the bamboo. In the areas where trees were not lost during flooding, the bending stress σ_f acting on the flood defense forest is less than 6.1 kN/cm^2, the stress necessary to bend, break or remove the bamboo. The comparison between flood results and experimental results confirm that 6.1 kN/cm^2 can be used as an index in determining flood defense forest lodging by floods.

4.2 Possibility of lodging the flood defense forest on the current river channel
We conducted a 2-D flow analysis using a probability scale (1/30 to 1/200) on the current river channel and evaluated the flood defense forest situation for the Tazu district, which is an undeveloped embankment area.

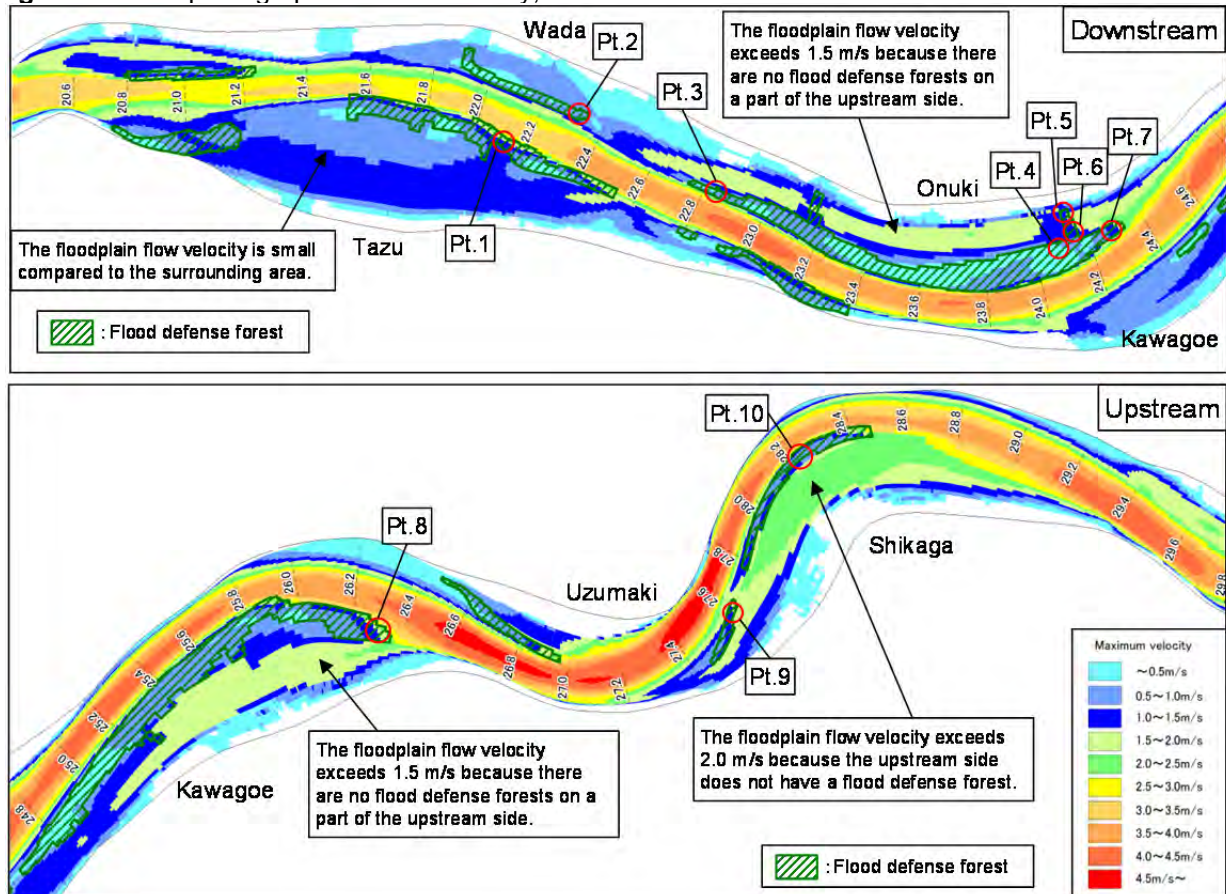**Figure 6**. Aerial photograph after flood in July, 1988 and assessment of the flood defense forest after flood

Figure 7. Maximum flow velocity plan from the flood reproduction calculation for July, 1983
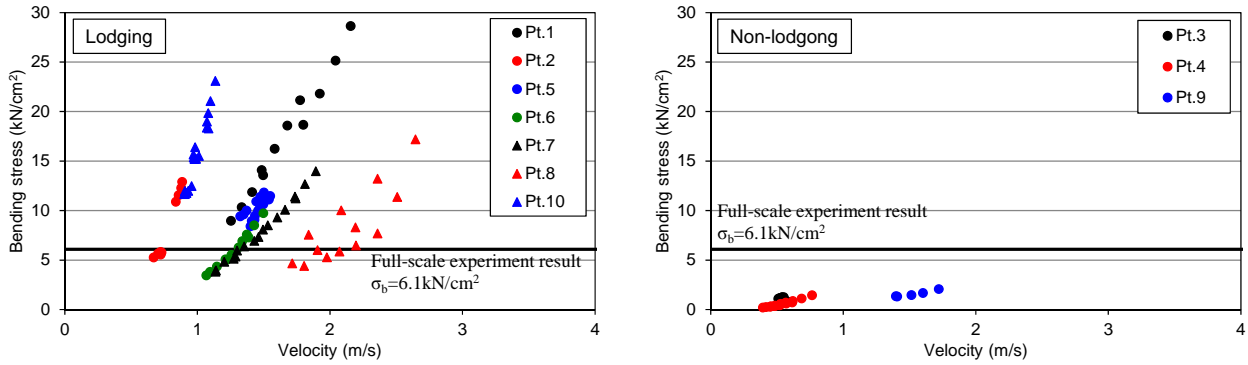
Figure 8. Bending stress level acting on the flood defense forest

Table 4. Bending stress calculated from average hydraulic quantity

Pt.	Position	Lodging situation	Diameter (cm)	Average hydraulic quantity		Bending stress (kN/cm²)
				Velocity (m/s)	Water depth (m)	
1	Left bank 22.1 km	Lodging	12	1.66	13.04	16.9
2	Right bank 22.4 km	Lodging	6	0.78	9.55	8.0
3	Right bank 22.8 km	Non-lodging	6	0.54	4.81	1.0
4	Right bank 24.0 km	Non-lodging	6	0.54	3.53	0.5
5	Right bank 24.1 km	Lodging	6	1.45	5.80	10.2
6	Right bank 24.1 km	Lodging	6	1.28	5.02	5.9
7	Right bank 24.3 km	Lodging	6	1.48	4.92	7.6
8	Left bank 26.4 km	Lodging	9	2.13	5.22	7.9
9	Left bank 27.6 km	Non-lodging	12	1.53	4.31	1.6
10	Left bank 28.2 km	Lodging	6	1.00	15.54	15.5

4.2.1 Analysis conditions

For the topography analysis, we used survey results from 2010 and an analysis mesh subdivided to extract hydraulic quantity in the flood defense forest in more detail. For external forces, the water discharge was set using a probability scale (Table 5).

Table 5. Water discharge by probability scale

Return period	Water discharge (m³/s)	
	Gotsu St.	Target section
1/30	8,300	7,800
1/50	9,300	8,700
1/100	10,700	10,000
1/200	12,500	11,800

4.2.2 Analysis results

In the probability scales of 1/30 and 1/50, the fluid force acting on the flood protection forest is small, so it is estimated that the flood defense forest will not be dislodged except for a part of the low flow channel side. Because the retention range of the flood defense forest continues in the longitudinal direction, it is possible to utilize the flow velocity reduction effect from the flood defense forest.

With a probability scale of 1/100, there is a possibility that the width of the slit upstream of the flood defense forest will expand due to forest lodging. One issue with the flood defense forest in the lower reach of the Gounokawa River is that the local flood plain flow velocity will increase due to the flow inundation from the slit on the upstream side. If the slit width expands due to the bamboo lodging, additional flood flows may increase the floodplain flow rate.

On the probability scale of 1/200, there is a possibility that the flood defense forest on the upstream side is totally lodged. In addition, because approximately 3/4 of the flood defense forest in the Tazu district is lodged, there is a possibility that the flow rate reduction effect from the flood defense forest will be lost.

When the flood defense forest is left with a width of 20 m, even if the same water discharge flows compared with the current width, it is considered that the lodging area ratio increases because the width of the flood defense forest is narrow.
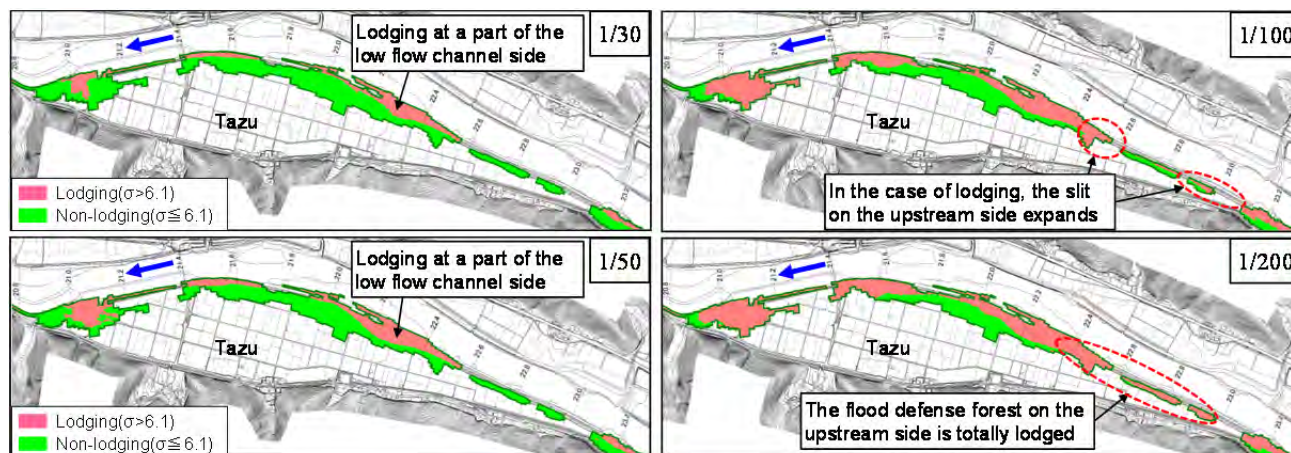
Figure 9. Plan view of lodging situation of flood defense forest (current width)

Table 6. Lodging area of flood defense forest

Return period	Area (ha)		Ratio	
	Lodging	Non-lodging	Lodging	Non-lodging
1/30	4.02	9.94	28.8%	71.2%
1/50	5.52	8.45	39.5%	60.5%
1/100	8.35	5.62	59.8%	40.2%
1/200	10.09	3.87	72.3%	27.7%

5   CONCLUSIONS

We were able to confirm the effectiveness of flood defense forests for cases where the forest widths are more than 20 m. The growth range and width are important factors in flood control and we examined the management policy that can be utilized to improve river protection and security.

In floods with high flood discharge, the numerical analysis results showed that more than half of flood defense forests are lodged, and the water velocity within the floodplain increases. When the flood defense forests are completely bent, damaged or removed, the water velocity in the floodplain is high enough to increase flood hazards. Therefore, it is necessary to manage flood risk assuming flood defense forests are rendered useless in large-scale floods.

Because we focused on flow velocity in the floodplain in this study, we did not consider the influence of river bed fluctuations. In order to investigate the influence of the flood plain on sediment deposition in detail, it is necessary to calculate river bed variations.

We investigated flood defense forest lodging effects in the lower reaches of the Gounokawa River for the historical flood in July, 1983, but it is still necessary to investigate future flooding. In addition, gathering and analyzing information concerning flood defense forest behavior during flooding is also important for other rivers.

ACKNOWLEDGMENTS

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