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# ASSESSING VEGETATION RESISTANCE FROM OBSERVED TEMPORAL WATER SURFACE PROFILES OF FLOOD FLOWS IN RIVERS

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## ABSTRUCT

The behavior of temporal change in water surface profiles manifests any hydraulic phenomena in river course resulting from cross-sectional change, resistance of vegetation and river bed variation during floods. Vegetation permeability coefficients and Manning's roughness coefficients for flood flows are estimated by unsteady two-dimensional flow analysis and observed data of temporal water surface profiles. Characteristics of vegetation resistance affected by vegetation conditions and channel scales were clarified using these computed results. The method for assessing the vegetation resistance is presented from analytical results using observed temporal water surface profiles.

***Key Words:*** *river management, vegetation permeability coefficient, Manning's roughness coefficient, characteristics of vegetation resistance, unsteady two-dimensional flow analysis*

## 1．INTRODUCTION

Vegetations play a significant role in channels to reduce impacts of flood flow on banks and form river environment and ecosystem. On the other hand, vegetations produce local high velocity near banks and increase in water levels. Therefore, vegetations are important for both flood control and river environment (Fukuoka 2005). Fukuoka and Fujita (1998) investigated in detail hydraulic effects of vegetations on flood flow by flume experiments. Similarly, many studies have been done on flow with vegetation in relation with river management.

The resistance to flood flow in rivers consists of vegetation resistance and channel bottom resistance which are included in the equations of motion of the two-dimensional flow as follows.

$$\left(\tau_s, \tau_n\right) = \left(\frac{gn^2}{h^{1/3}} + \frac{gh_a}{K^2}\right)\sqrt{u^2 + v^2}\left(u, v\right) \tag{1}$$

Where, $K$ = vegetation permeability coefficient; $n$ = Manning's roughness coefficient; $h$ = water depth; $h_a$ = min($h$, $h_{tree}$); $\left(u,v\right)$ = velocity components$\left(s,n\right)$. In the conventional two-dimensional non-uniform flow analysis, some problems arise in the estimation of the flow resistance by two reasons: one is for observation errors of water discharge and flood trace levels and the other is for the method of analysis. Vegetation permeability coefficients, therefore, differ from every flood. Fukuoka and Watanabe (2006) developed on unsteady two-dimensional flow analysis method with observed temporal water surface profiles, which represents well the essential characteristics of flood flow. In this unsteady flow analysis, vegetation permeability coefficient and Manning's roughness coefficient were determined reasonably for flood flow. The authors showed that Manning's roughness coefficient was independently given by geometry and boundary resistance of rivers, irrespective of vegetation conditions. Then, the vegetation permeability coefficients are determined by the unsteady two-dimensional flow analysis so as to reproduce the observed temporal water surface profiles of flood flows (Fukuoka and Fujisawa 2007a, Fukuoka and Sato 2007b).

In this study, vegetation resistance characteristics during flood are investigated from the unsteady two-dimensional flow analysis (Fukuoka and Watanabe 2006, Fukuoka and Fujisawa 2007a, Fukuoka and Sato 2007b). Then, vegetation permeability coefficients corresponding to channel's scales and vegetation conditions are examined. Finally water levels and velocity vectors are used for indices of an assessment method of rivers with vegetations.

## 2 . CONDITIONS OF CHANNELS AND VEGETATIONS

The area studied in the Tone River (104.0km-131.0km) is shown in Figure 1. Figure 2 shows observation reach in the Watarase River (3.0km-5.5km). The Watarase River is one of the tributaries of the Tone River and joins the Tone River at 132.5km. There are vegetations, mainly willow, on flood channel throughout those areas and most of them are higher than bank crown level. Fukuoka and Watanabe (2006) conducted the two-dimensional analysis for several floods in the Tone River and Edo River. In this paper, based on their results, we investigate vegetation resistance in the Tone River on September, 1998 and the Watarase River on September, 2007. Recent major floods in the Tone River and Edo River are shown in Table 1, including heavy floods in 1998 and 2007. Cross-sectional shape at 130.0km in the Tone River and observed water levels are shown in Figure 3. Since the Tone River has had no heavy floods from 1982 to 1998, willows on flood channel grew up so high. Then, the vegetation become a main resistance element to flood flows.

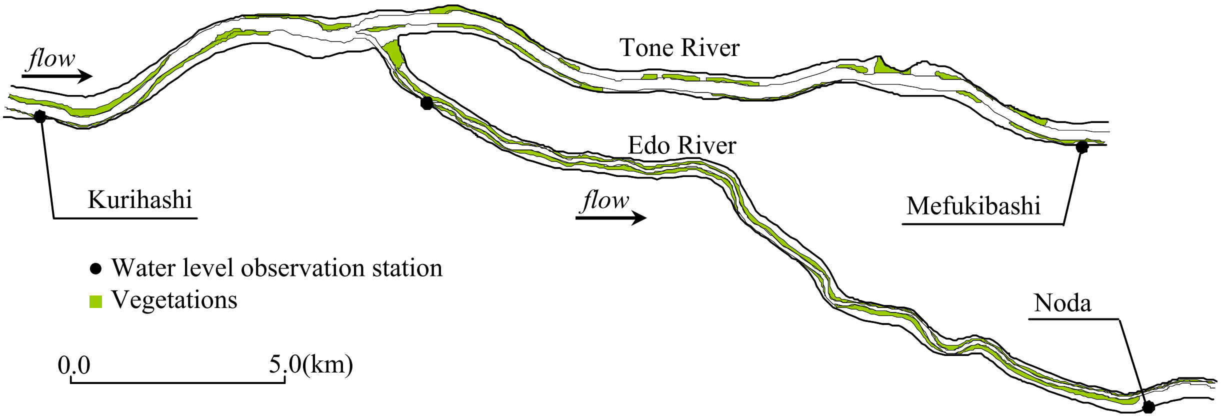


Figure 1 Planform and channel conditions of the studied areas of the Tone River and Edo River.

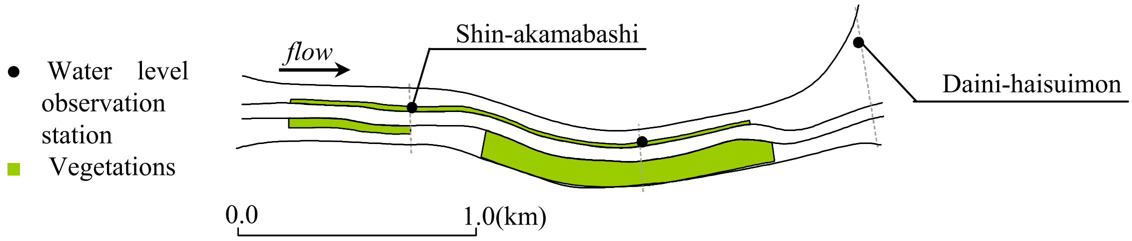


Figure 2 Planform and channel condition of the studied area of the Watarase River.

Table 1 Recent major floods in the Tone River and Edo River.

| Year/ Month | Typoon No. | Observed maximam water discharge($m^3$/s) | |
|---|---|---|---|
| | | Kurihashi (Tone R.) | Noda (Edo R.) |
| 1982/ 9 | 18 | 11,606 | 2,872 |
| 1998/ 9 | 5 | 10,431 | 2,449 |
| 2001/ 9 | 15 | 7,980 | 2,020 |
| 2002/ 7 | 6 | 8,555 | 1,622 |
| 2004/ 10 | 22 | 4,563 | 1,333 |
| 2004/ 10 | 23 | 4,025 | 1,210 |
| 2007/ 9 | 9 | 8,933 | 1,934 |

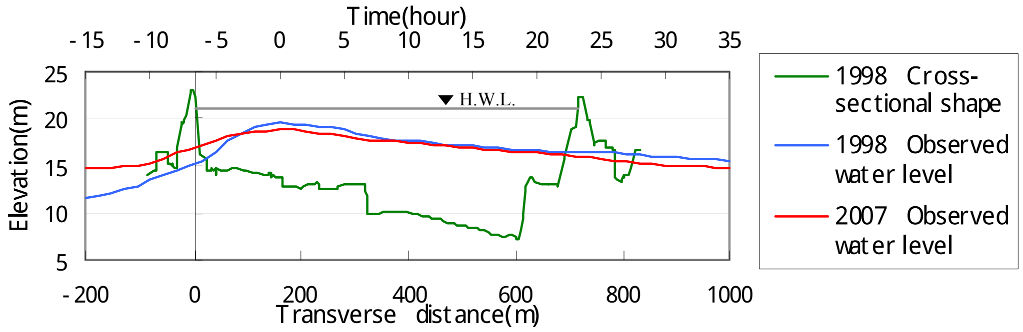
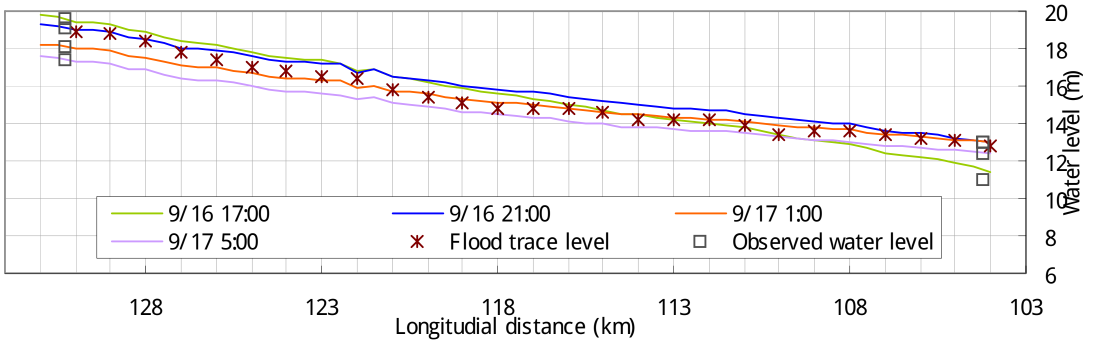
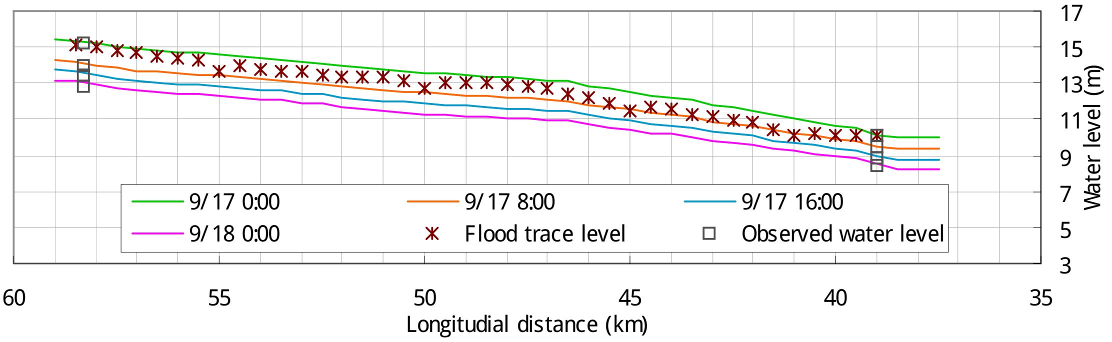


Figure 3 Observed water levels and cross-sectional shape at 130.5km in the Tone River.



(a) Tone River



(b) Edo River

Figure 4 Computed temporal water surface profiles and observed water levels for flood in 1998.

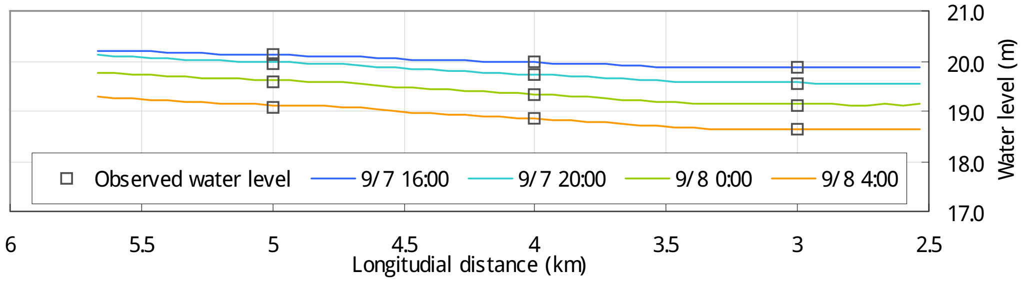


Figure 5 Computed temporal water surface profiles and observed water levels for flood in the Watarase River in 2007.

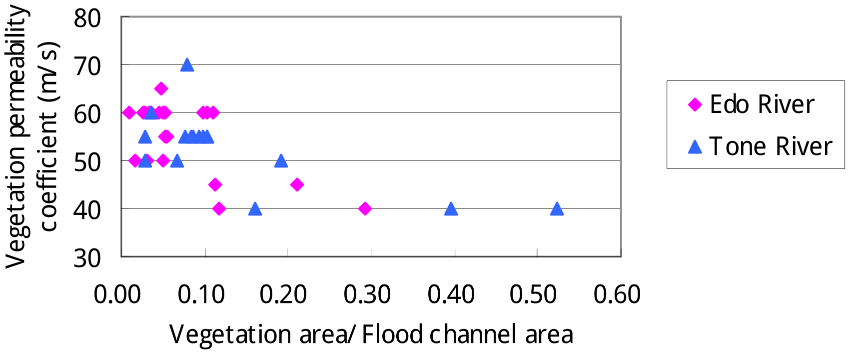


Figure 6 Relationship between vegetation permeability coefficient and the ratio of vegetation area to flood channel area.

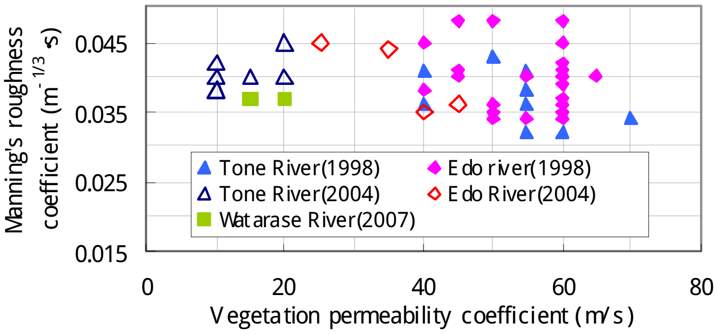


Figure 7 Relationship between vegetation permeability coefficient and Manning's roughness coefficient.

Vegetation permeability coefficients $K$ are determined by the unsteady two-dimensional flow analysis so that observed water surface profiles coincide well with calculated ones (Figure 4, Figure 5). Figure 6 shows the relationship between vegetation permeability coefficient and the ratio of vegetation area to flood channel area for the 1998 flood. It shows that vegetation permeability coefficient is smaller as the ratio of vegetation area to flood channel area is larger. Since, the vegetation resistance expressed in Eq. (1) becomes large when vegetation permeability coefficient is small, vegetation resistance become larger as the ratio of vegetation area to flood channel area is larger. The relationship between vegetation permeability coefficient and Manning's roughness coefficient is shown in Figure 7. Small-scale flood in 2004 is also included in Figure 7. Since, reeds on flood channel were main resistance element to 2004 flood flows, vegetation permeability coefficients are small in comparison with those of the other floods. Tables 2-4 shows characteristics of vegetation and channel. Those data are used in the later investigation.

## 3． RESISTANCE CHARACTERISTICS OF VEGETATIONS ON FLOOD FLOWS

Vegetations in rivers decrease the cross-sectional velocity by mixing flows within the vegetation area and flow outside vegetations and increase the flow resistance. Vegetation resistance seems to be related to the scale of channel as well as vegetation conditions. The vegetation resistance to flood flow may be explained by vegetation permeability coefficients $K$ by solving unsteady two-dimensional flow equations.

For describing the relation of channel scale and vegetation scale, the ratio of vegetation width to channel width and the ratio of vegetation resistance term to sum of all the terms in the equations of motion at the time of peak discharge are chosen on the coordinate of Figure 8. It shows that the ratio of vegetation resistance term to sum of all the terms in the equations of motion of the Watarase River is greater than other larger rivers, although the

Table 2 Channel and vegetation properties in the Tone River.

| Vegetation | Vegetation width: $B_w$ (m) | Main channel width:$B_{mc}$(m) | Channel width: B (m) | $B_w/B$ | $B_w/B_{mc}$ | $B_{mc}/B$ | K (m/s) |
|---|---|---|---|---|---|---|---|
| T-R-1 | 12 | 207 | 740 | 0.02 | 0.06 | 0.28 | 70 |
| T-R-2 | 51 | 291 | 658 | 0.08 | 0.18 | 0.44 | 70 |
| T-R-3 | 92 | 313 | 701 | 0.13 | 0.29 | 0.45 | 55 |
| T-R-4 | 38 | 274 | 565 | 0.07 | 0.14 | 0.49 | 60 |
| T-R-5 | 56 | 255 | 545 | 0.10 | 0.22 | 0.47 | 55 |
| T-R-6 | 7 | 296 | 511 | 0.01 | 0.02 | 0.58 | 50 |
| T-R-7 | 57 | 223 | 537 | 0.11 | 0.26 | 0.41 | 50 |
| T-R-8 | 32 | 246 | 523 | 0.06 | 0.13 | 0.47 | 50 |
| T-L-1 | 169 | 210 | 709 | 0.24 | 0.81 | 0.30 | 55 |
| T-L-2 | 83 | 339 | 773 | 0.11 | 0.24 | 0.44 | 40 |
| T-L-3 | 90 | 347 | 965 | 0.09 | 0.26 | 0.36 | 40 |
| T-L-4 | 78 | 271 | 535 | 0.15 | 0.29 | 0.51 | 40 |
| T-L-5 | 61 | 254 | 541 | 0.11 | 0.24 | 0.47 | 55 |
| T-L-6 | 80 | 253 | 499 | 0.16 | 0.32 | 0.51 | 55 |
| T-L-7 | 81 | 264 | 525 | 0.15 | 0.31 | 0.50 | 55 |
| T-L-8 | 66 | 302 | 525 | 0.13 | 0.22 | 0.57 | 55 |
| T-L-9 | 75 | 279 | 507 | 0.15 | 0.27 | 0.55 | 55 |
| T-L-10 | 105 | 285 | 575 | 0.18 | 0.37 | 0.50 | 55 |
| T-L-11 | 38 | 243 | 578 | 0.07 | 0.15 | 0.42 | 55 |

Table 3 Channel and vegetation properties in the Edo River.

| Vegetation | Vegetation width: $B_w$ (m) | Main channel width:$B_{mc}$(m) | Channel width: B (m) | $B_w/B$ | $B_w/B_{mc}$ | $B_{mc}/B$ | K (m/s) |
|---|---|---|---|---|---|---|---|
| E-R-1 | 55 | 110 | 347 | 0.16 | 0.50 | 0.32 | 55 |
| E-R-2 | 80 | 94 | 353 | 0.23 | 0.86 | 0.27 | 50 |
| E-R-3 | 76 | 91 | 374 | 0.20 | 0.83 | 0.24 | 50 |
| E-R-4 | 123 | 65 | 356 | 0.35 | 1.91 | 0.18 | 60 |
| E-R-5 | 48 | 95 | 353 | 0.14 | 0.51 | 0.27 | 40 |
| E-R-6 | 87 | 81 | 344 | 0.25 | 1.07 | 0.24 | 65 |
| E-L-1 | 66 | 108 | 346 | 0.19 | 0.61 | 0.31 | 60 |
| E-L-2 | 54 | 100 | 350 | 0.15 | 0.54 | 0.28 | 60 |
| E-L-3 | 65 | 87 | 371 | 0.18 | 0.75 | 0.24 | 60 |
| E-L-4 | 118 | 108 | 363 | 0.33 | 1.09 | 0.30 | 60 |
| E-L-5 | 81 | 102 | 360 | 0.23 | 0.80 | 0.28 | 40 |
| E-L-6 | 91 | 87 | 354 | 0.26 | 1.05 | 0.24 | 45 |
| E-L-7 | 60 | 80 | 348 | 0.17 | 0.76 | 0.23 | 60 |

Table 4 Channel and vegetation properties in the Watarase River.

| Vegetation | Vegetation width: $B_w$ (m) | Main channel width:$B_{mc}$(m) | Channel width: B (m) | $B_w/B$ | $B_w/B_{mc}$ | $B_{mc}/B$ | K (m/s) |
|---|---|---|---|---|---|---|---|
| W-R-1 | 37 | 62 | 241 | 0.15 | 0.59 | 0.26 | 15 |
| W-R-2 | 110 | 61 | 239 | 0.46 | 1.80 | 0.26 | 15 |
| W-L-1 | 15 | 61 | 239 | 0.06 | 0.24 | 0.26 | 20 |

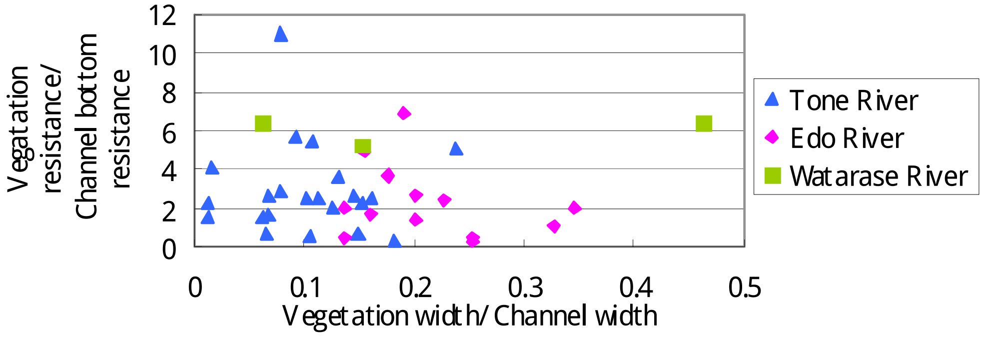


Figure 8 Relationship between vegetation resistance and channel scale at the time of peak discharge.

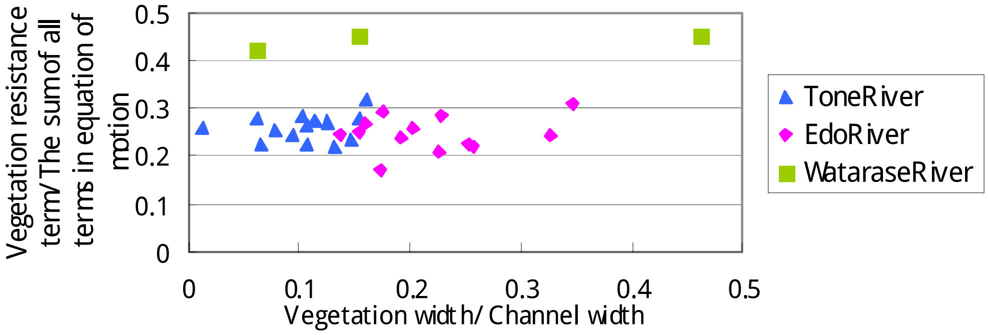


Figure 9 Relationship between vegetation resistance and bed resistance against channel scale at the time of peak discharge.

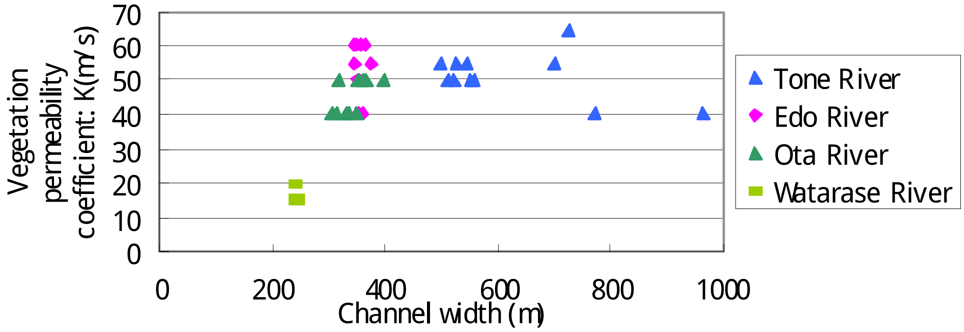


Figure 10 Relationship between channel width and vegetation permeability coefficient.

ratio of vegetation width to channel width is within the same range. This is because the vegetation in smaller channel such as the Watarase River affects strongly on flood flow. Figure 9 shows the relationship between the ratio of vegetation width to channel width and the ratio of vegetation resistance to channel bed resistance in each river. The ratio of vegetation resistance to channel bed resistance in the Watarase River is greater than the others. Figure 10 shows the relationship between vegetation permeability coefficient and scale of channel in the Tone, Edo, Watarase and Ota Rivers (Gotoh and Fukuoka, 2007c). Values of vegetation permeability coefficient tend to decrease as the channel width is smaller. It means that the vegetation resistance increases relatively in smaller channels.

It is shown that the unsteady two-dimensional flow analysis using observed water surface profiles during floods provides a good explanation for vegetation resistance represented by the vegetation permeability coefficient in rivers.

## 4． METHOD FOR ASSESSING EFFECTS OF VEGETATIONS ON FLOOD FLOW

Longitudinal distribution of water level is the most important index to understand channel condition for the flood control. The method for assessing vegetation effect was investigated in 123.0km-129.0km of the Tone River shown in Figure 11. Figure 12 shows calculated water surface profile of peak discharge for the 1998 flood estimated by the

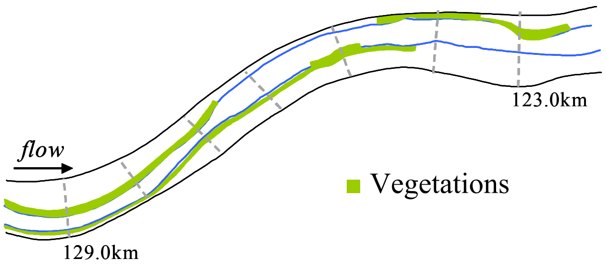


Figure 11 Planform and channel condition of the observed area of the Tone River.

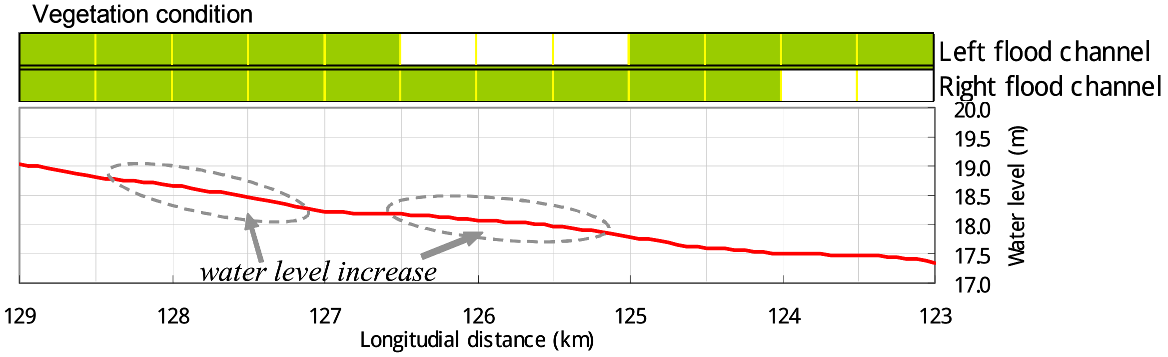


Figure 12 Observed water level and vegetation distribution.

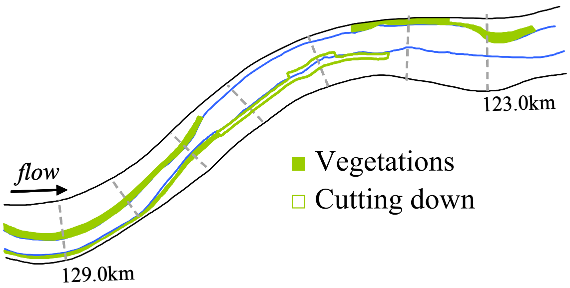


Figure 13 Planform and channel condition of the observed area (Case1).

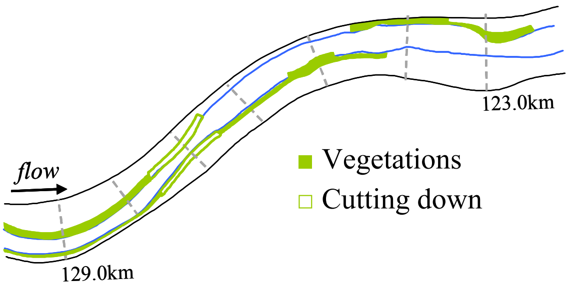


Figure 14 Planform and channel condition of the observed area (Case2).

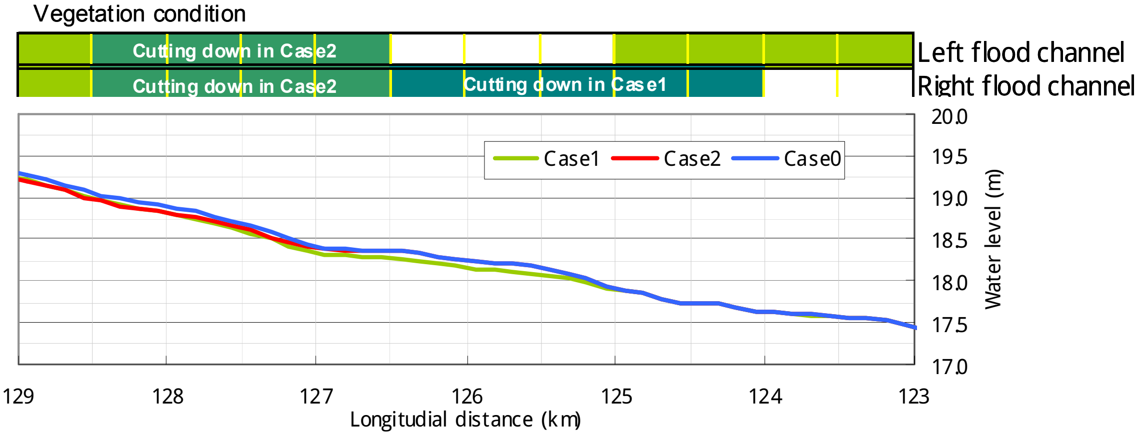


Figure 15 Calculated water levels and vegetation distribution.

unsteady two-dimensional flow analysis (Case0). From Figures 11 and 12, the computed water level increases in 125.5km and 127.5km, which seems to be caused by resistance of vegetations on right flood channel in 124.5km-125.5km and by contracted section of main channel in 126.5-127.5km.

Based on the unsteady two-dimensional flow analysis, vegetation effect on flood flow is investigated from water surface profiles and velocity fields. Here, Case 1 and Case 2 simulated by altering vegetation permeability coefficient evaluate the influences of cutting down at the right flood channel in 124.5km-126.5km (Figure 13) and both flood channels in 126.5-127.5km (Figure 14), respectively. The unsteady two-dimensional flow analysis by Fukuoka and Watanabe (2004) proved to be a useful method for determine the vegetation permeability coefficients and evaluating precise temporal water discharges at any point. Here, the temporal water discharge is given as the boundary condition at upstream end instead of observed temporal water level flow simulations of cutting down because water level changes by cutting down.

Figure 15 shows the comparison between computed water surface profiles at each peak discharges of Case 1, Case2 and Case 0 and decreases in water levels by the cutting down. Decrease in water level is about 10cm in Case1 and 5cm in Case 2 at the upstream of vegetations in objective. Figure 16 and Figure 17 show differential velocity vectors from velocity vector of Case 0. In those figures, blue arrow shows that the velocity difference is 0.0m/s-0.3m/s, and red ones above 0.3m/s. Both cases show velocity increase in cutting down area. Figure 16 shows velocity difference of Case 1 from the velocity of Case 0. Velocity vectors increase at the boundary of main channel and right flood channel and decrease in main channel and left flood channel in 124.5km-125.5km. It seems to reduce flow velocity toward left flood channel in 124.0km-126.0km. Figure 17 shows velocity difference of Case 2

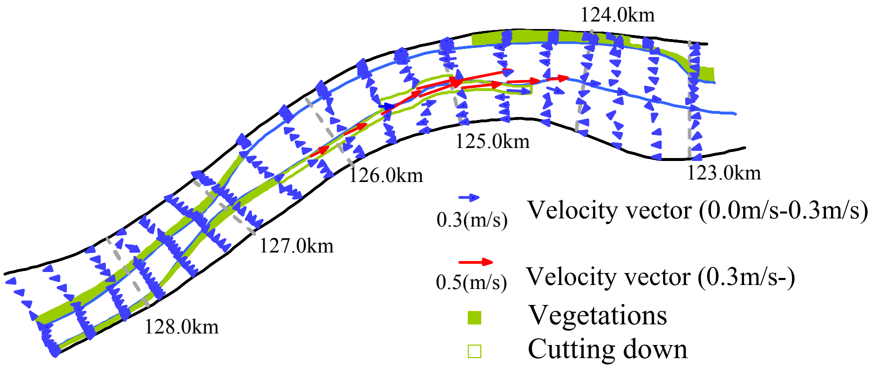


Figure 16 Computed differential velocity vector field (Case 1 –Case0).

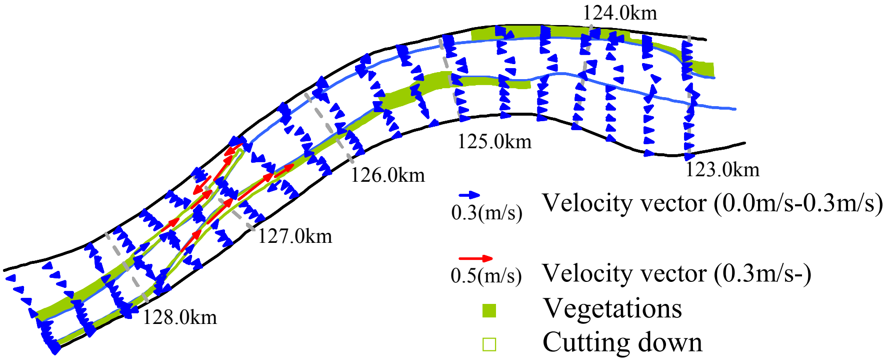


Figure 17 Computed differential velocity vector field (Case2 –Case0).

from Case 0 and velocity increase at main channel contracted section in cutting down areas and velocity decrease on flood channel at the end of contracted section. The latter is caused by turbulent mixing of the activated flow at the boundary of flood channel and flows on flood channel.

The effects of vegetation on flood flow are clarified by the flow simulation of cutting down. Significant change in longitudinal distribution of water levels (water surface profiles) and velocity vectors is confirmed by this analysis method.

## 5 . CONCLUSIONS

The authors investigated vegetation resistance characteristics and a method for assessing vegetation effect on flood flow in the Tone River, Edo River and Watarase River on the basis of unsteady two-dimensional flow analysis using observed temporal water surface profiles. The primary conclusions in this research are as follows.

(1)In river with vegetations, Manning’s roughness coefficient is determined by boundary shape of channel and then, vegetation permeability coefficient is determined by the unsteady two-dimensional flow analysis so as to reproduce the observed temporal water surface profiles. Flow resistance determined by this method provides a reasonable explanation for river flow with vegetations.

(2) Ratio of vegetation resistance term to sum of all terms in the equations of motion increases in smaller channel even though the ratio of vegetation width to channel width is almost the same. And so is the ratio of vegetation resistance to channel bed resistance.

(3)Vegetation permeability coefficients decrease as channel scale becomes small.

(4)Vegetation effect on flood flow was assessed by simulating the flow of cutting down altering vegetation permeability coefficient and using temporal water discharge as boundary condition at upstream end. It is shown that water levels and velocity vectors are useful as the indices of the assessment of the flow with vegetations.

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