FLOOD SIMULATION MODEL COUPLED WITH WOODY VEGETATION WASH-OUT IN THE LOWER ASAHI RIVER, JAPAN

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ABSTRACT

Flooding with a discharge of approximately 4500 m^3/s occurred in the lower Asahi River because of the heavy rain event in western Japan in July 2018. This flooding engendered wash-out situation of vegetation such as woody and herbaceous species and lodging of bamboo grove. Earlier research works attempted to clarify the critical wash-out condition of woody vegetation during flooding. However, two challenges still need to be solved: (1) the tractive force and moment because of drag force acting on woody vegetation, were estimated assuming without vegetation was washed out, and (2) the mechanism of woody vegetation wash-out was evaluated considering only a unique parameter of either the tractive force or moment, but not the both. Accordingly, the critical wash-out condition in the lower Asahi River in 2018 was not reasonably elucidated by the earlier frameworks. Considering those limitations, this study proposed a novel numerical simulation model for the woody vegetation wash-out in rivers during flooding. The mechanism of the flow resistance reduction because of the woody vegetation wash-out was also taken into consideration. In this study, vegetation conditions and topo-bathymetric data were accurately extracted using an airborne laser bathymetry (ALB) system for the targeted domain in the lower Asahi River. The simulated results demonstrated that the proposed model can improve the reproducibility of the wash-out situation after the flooding, compared with models that did not incorporate both the woody vegetation height distribution and transition process of woody vegetation wash-out during flooding.

Keywords: Flooding, vegetation wash-out, critical condition, Airborne Laser Bathymetry

1. INTRODUCTION

Due to the heavy rain in western Japan in July 2018, the catastrophic flood damage occurred in a wide range. Especially, in Oda River, the right branch of the Takahashi River flowing across Okayama prefecture, several levees were breached, and many lives were lost at Mabi district in Kurashiki city. The main factor of the embankment collapse is the backwater effect due to the rapid rise in the water level of the Takahashi River, but as shown in Figure 1, the trees are densely grown in the river channel, and the effects of impeded water flow are being studied.

Figure 1. Breach of a levee and the vegetation flourish situation at 3.4 KP of the Oda River; where the kilometre post (KP) value signifies the longitudinal distance (km) from the river mouth (Okayama River Office, July 8, 2018).

When trees in the river channel are densely grown as a community, there is a great concern that the flood flow resistance will be higher during floods, reducing the flood capacity. In addition, there are also flood control problems, such as blockage of the bridge as driftwood, flooding, and damage to houses. Therefore, it is necessary to elucidate the wash-out mechanism of trees and predict the wash-out location in the river channel. In the past research works, regarding the wash-out phenomena of trees, the condition of wash-out limit has been studied in relation to the fluid force acting on the vegetation and the tractive force. For example, Tanaka et al. (2009) clarified the difference in the limit of wash-out of trees at different locations on a gravel basin based on the wash-out of trees during flooding. In addition, Iimura et al. (2017) revealed the effects of flooding on vegetation in the Kinu River using the relationship between vegetation loss and friction speed and bending moment from the observations conducted by UAV (unmanned aerial vehicle), GIS (geographic information system) and hydraulic analysis. In the conventional research, because the flow condition analysis at the peak flow rate was performed without vegetation wash-out, and the fluid force and the tractive force were examined, the surrounding flow field due to wash-out cannot be considered. As a result, when examining the actual wash-out limit, it is possible to estimate relatively small fluid forces acting on dense trees as limit values. Conversely, in the case of a large-scale flood, trees may flow out before the peak time, and in that case, there is a possibility that relatively large fluid force or tractive force will be evaluated as the limit value.

In the Asahi River, target study area flowing across Okayama city, a flood with a peak flow of 4500 m^3/s occurred on the dawn of July 7, 2018, due to heavy rain in western Japan. But, the Asahi River and its diversion, the Hyakken River avoided the river damage due to the river improvement works such as the diversion weirs in embankment. However, there has been a great concern over flood control due to forestation of river channels, and proper management of vegetation in river channels is desired. On the other hand, since the floods in the lower reach of the Asahi River were relatively large floods, the wash-out of trees and herbs was observed in the Nakahara and Gion areas in the downstream part. Therefore, in this study, in order to elucidate the wash-out mechanism of vegetation during flooding, the field surveys and flood flow analysis were conducted for both areas. The numerical results of this study particularly provide useful information to improve the reproducibility of the vegetation wash-out phenomenon by setting the wash-out limit condition through focusing on vegetation height and tractive force and incorporating the resistance reduction due to vegetation wash-out in the flood flow analysis.

2. AIRBORNE DATA COLLECTION AND FIELD MESERMENTS

2.1 Extraction of riverbed and vegetation data by ALB measurement

2.1.1 Overview of ALB measurements and target intervals

ALB measurement was performed in the target area (as shown in Figure 2; the Asahi River: 8.6 KP-17.4 KP, the Hyakken River: 11.4 KP-Diversion weir) of this study in November 2017 and January 2018 before the target flood. The measurement instrument specifications and measurement conditions are presented in Table 1.

Table 1. Instrument specifications and conditions for ALB measurements.

Measurement time	**Equipment specifications**	**River turbidity* (kaolin suspension)**
2016.03	Leica Chiroptera II (Infrared 0.5 m x 0.5 m for 2 or more points, 2 points or more at 1.0 m x 1.0 m green line)**	2.8°
2017.03		2.9°
2017.11		3.2°
2018.01		no data

*Hydrological Water Quality Database (Asahi River, Otoizezeki Water Quality Observatory), **Measurement density

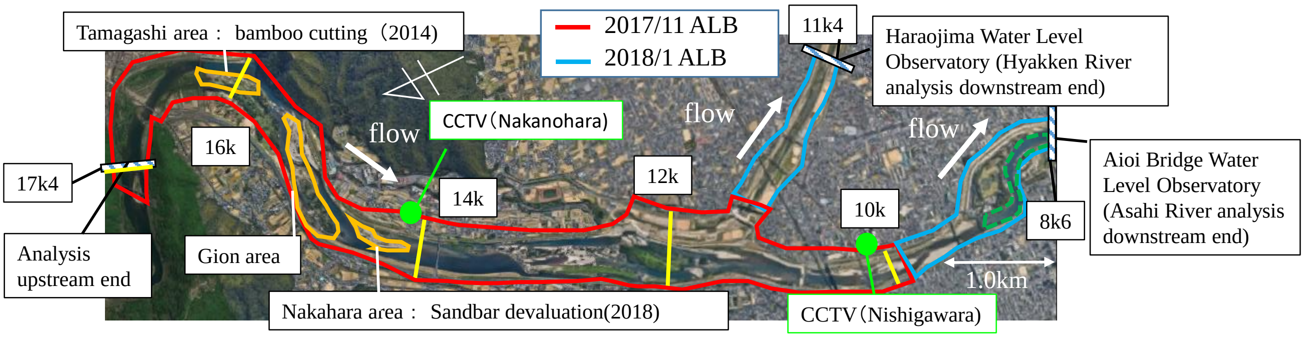

Figure 2. ALB data acquisition range in the target study area.

Comparing to the previous measurement in March 2016 and March 2017, the river condition is generally consistent in both measurements, and the calculation performance of the vegetation characteristics is considered to be the same. Due to the reason for data processing, there was no data on vegetation characteristics in January 2018 (target areas, the Asahi River: 8.6 KP-9.8 KP, the Hyakken River: 11.6 KP-12.8 KP), therefore, based on the history of the previous ALB data processing, a manual decision was made considering field surveys and aerial photographs and finally, the data was created.

2.1.2 Classification of ground covers and vegetation species

As with previous studies, clustering was performed on the ALB point cloud data contained in the 2 m mesh, and the river was divided into water, bare, and vegetation areas, and vegetation was classified into herbs, trees, and bamboo forests. Figure 3 depicts a comparison on the classification of ground covers and vegetation species based on ALB data, and ortho-image taken by drone before flooding, and it was observed that vegetation classifications were almost consistent. However, the place surrounded by a yellow frame in the ortho-image (Figure 3) was misjudged as a tree in the newly settled short bamboo forest (Figure 4). Correspondingly, the vertical structure of the ALB point cloud is considered to be different compared to the existing bamboo forest, but the details are unknown. Therefore, a classification diagram was manually created. Figure 5 shows the longitudinal variation in the occupancy rate of the vegetation classification in the target river. The occupancy rate was estimated by the percentage of the target vegetation species on the sandbar. It was elucidated that bamboo forests were often observed in 12.4 KP and 16.5 KP (Tamagashi area), in addition, trees were relatively growing in the upper reaches of 14 KP.

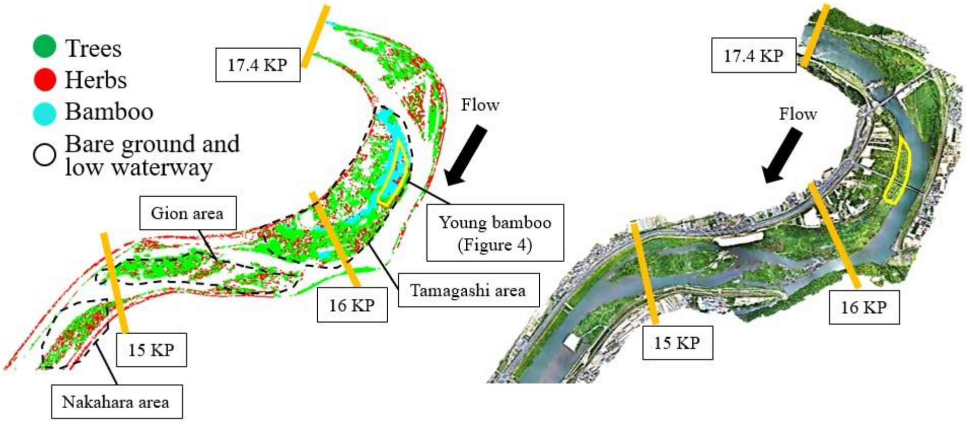

Figure 3. Classification by ALB data (left), and ortho-image (right) before flooding (May 2018) in Asahi River (14.5 KP-17.4 KP).

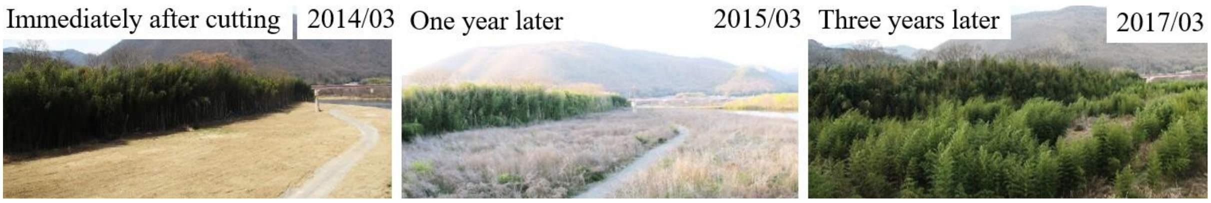

Figure 4. Photographs of short bamboo forests newly invaded after logging in the Tamagashi area.

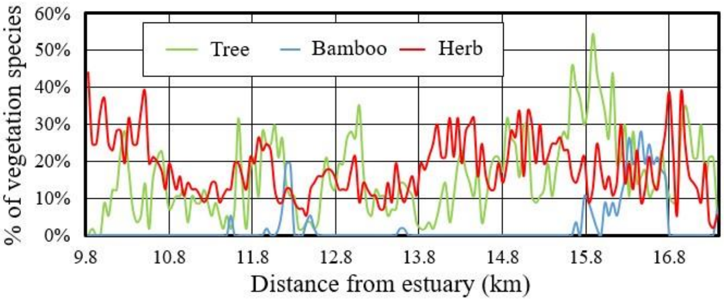

Figure 5. Variation in the occupancy rate of vegetation species along the reach of the target river.

2.2 Local inspection

After the flood, the Nakahara, Gion and Tamagashi districts (Figure 3) were surveyed, and the remaining, lodging and wash-out conditions of vegetation were confirmed, and the riverbed level was measured in the water and land area in the low waterway. In addition, in order to confirm the vegetation situation in a wide area, an oblique photograph was also taken while flying low with a drone. Figure 6 shows the ortho-image, taken by drone, of the wash-out situation of the Asahi River after flooding (July 2018) and the survey site of the riverbed material. Also, Figure 7 depicts the lodging situation of the short-length bamboo forest observed in the Tamagashi area and the lodging situation of the trees observed in the Nakahara area. As a consequence, compared with the pre-flood situation, it can be elucidated that there were few damaged trees in lodging condition and a lot of vegetation was washed-out. In the following study, the correlation between the wash-out of tree and herbs in Gion and Nakahara areas and the hydraulic quantity during flooding was focused, and a simple model of vegetation wash-out was examined.

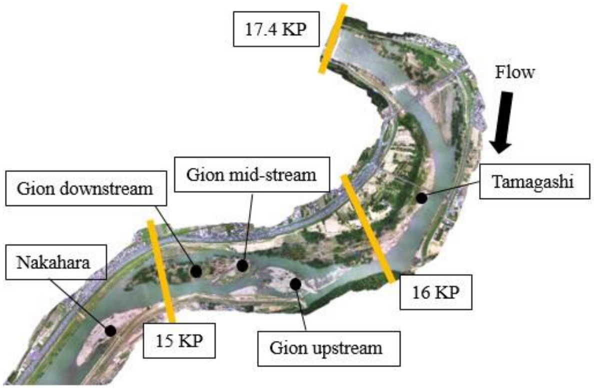

Figure 6. The wash-out situation of the Asahi River after flooding and the investigation point of the riverbed material (●).

Figure 7. Photographs of vegetation condition after flooding (left: short bamboos in the Tamagashi area; right: the lodging of trees in the Nakahara area).

3. NUMERICAL ANALYSIS

3.1 Flood flow analysis

In the target area (Figure 2), a plane two-dimensional (2-D) analysis was performed for the flood flow observed from 18:00 on July 6 to 6:00 on July 8, 2018. The calculation grid was divided into boundary-fit meshs with 942 cross-sections in the longitudinal direction and 57 nodes in each cross-section of the Asahi River, and the Hyakken River comprised of 277 cross-sections in the longitudinal direction and 39 nodes in each cross-section. Accordingly, the average mesh size was around 10 m. In the target area, the river bed evolution of about 30 cm was observed on average due to the influence of the flood, but in this analysis, the river bed evolution was not considered because of its simplicity, and only the tractive force acting on the fixed riverbed was examined. As for the river bed evolution, there were few measurement points in this survey, but in our future research, it will be taken into consideration based on detailed surveying. The flow rate at the upstream end of Asahi River (19 KP) estimated from Shimomaki Observatory using a stage-discharge (H-Q) relation, the water level at the downstream end of Asahi River (8.6 KP) collected from Aioi Bridge Observatory, and the water level at the lower end of the Hyakken River (11.6 KP) obtained from Haraojima Observatory were elucidated in Figure 8, presenting water level and flow hydrograph used in the flood flow analysis.

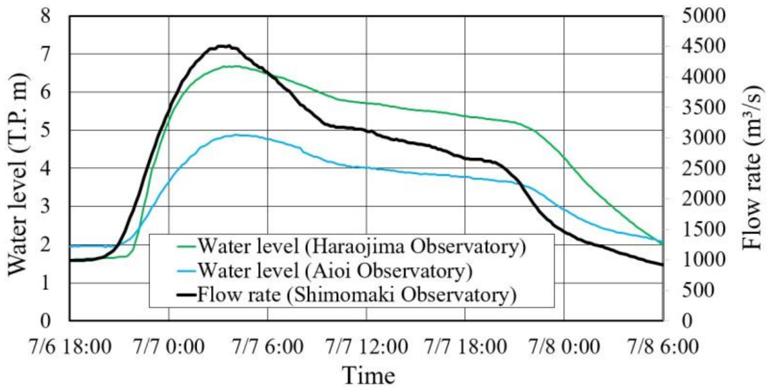

Figure 8. Observed water levels and estimated discharge during flooding in July 2018.

From the hydrograph, it was observed that peak flow rate at the upstream end of Asahi River was 4512 m^3/s recorded at 03:40 on July 7, 2018. For the riverbed level data, the results of the ALB survey (2 m square mesh) at the closest point were used for grid points in the flow analysis. However, due to the devaluation of the sandbars around Nakahara Bridge from 2017 to 2018, the ALB survey data shown above were different from the topography during the 2018 flood, so it was revised based on construction cross-sectional data. Then, referring to the earlier studies (Yoshida et al., 2019; Yoshida et al., 2017), the values of the Manning's coefficient in the low and high waterways were 0.028 and 0.026 $m^{-1/3}s$, respectively.

In the same way as the height and density of vegetation (Yoshida et al., 2017), the vegetation species were first specified for each ALB data (2 m square mesh). In other words, the vegetation height was obtained by subtracting the DTM (bed level or digital terrain model) value from the DSM (digital surface model) value. In addition, the density of vegetation was estimated using the ALB point cloud based on the results of the earlier report of Yoshida et al. (2018). The density of herbs and bamboo forests was taken as 0.031 and 0.286 m^{-1}, respectively (Yoshida et al., 2017). However, the density of the low-length bamboo forest in Tamagashi area was given as a provisional value of 0.02 m^{-1} based on the observation of the local inspection. Correspondingly, the abundance ratio of each vegetation species in the analysis grid unit and the sum of the flow resistance for each vegetation species were estimated (Yoshida et al., 2017).

3.2 Vegetation wash-out analysis

As a result of the flood flow analysis, the depth of water at each time and the average flow rate of the depth of water can be obtained. In addition, the non-dimensional tractive force τ_{*_i} and the non-dimensional critical tractive force $\tau_{*_{ci}}$ for each analysis grating, the drag F_k that works in the area including vegetation species k, and the rotational moment M_k based on the riverbed are required.

$$\tau_{*_i} = \frac{\tau}{\rho s g d_i} = \frac{u_*^2}{s g d_i}, \qquad F_k = \frac{1}{2}\rho C_{Dk}\lambda_k l_{\min,k} w_k u^2 \tag{1}$$

$$M_k = \frac{1}{2} F_k l_{\min,k}, \qquad l_{\min,k} = \min(l_k, h) \tag{2}$$

Where, s is the submersible specific gravity of soil particles, g is gravitational acceleration, τ is shear stress of the riverbed (evaluated by Manning's formula), d_i is the target particle size in the riverbed material, d_m is the average particle size of the riverbed material, $\tau_{*_{cm}}$ is non-dimensional critical tractive force for the average particle size, ρ is the density of water, λ is the density of vegetation, l is vegetation height, and w is the abundance of vegetation species (herb, tree and bamboo forest) in the mesh. In addition, the drag coefficient C_D was determined based on the earlier report of Maeno et al. (2005). In this study, only the vegetation species were considered for the moment. And, the riverbed grain size obtained from the field survey results was also used in the vegetation wash-out analysis (Figure 6).

4. RESULTS AND DISCUSSION

4.1 Comparison of simulated and observed water levels

At the time of the flood, the water surface was projected on the image of the CCTV (closed-circuit television) camera for river monitoring, and in this study, it was used to verify the accuracy of the flow condition reproduction of the flood flow analysis. The CCTV was considered at Nakanohara left bank (Asahi River, 13.8 KP) before the separate flow to the Hyakken River, and at the Nishigawara left bank (Asahi River, 10 KP) after the separate flow. In Nakanohara, the water level markers attached on the piers were visually read, and in Nishigawara, the water level of the opposite bank was visually read from the image. In Nishigawara, after the flood, the angle of view of CCTV was returned to the state at the time of the flood, and the survey was carried out on the opposite bank. Figure 9 compares the simulated water level at both points with the water level reading on CCTV. It was observed that the simulated water levels for both points were almost identical to the levels recorded on CCTV. Figure 10 shows the analysis results of the longitudinal water level of the left bank and the trace water level at the peak of the flood flow rate. The Tokyo Peil (T.P.) is the data level, used in this figure, represents the average sea level of Tokyo Bay in Japan. In the analysis, two vegetation conditions were examined, whereas one was estimated from ALB data before the flood. The other was to manually determine the vegetation height to 0, taking into account the wash-out and lodging conditions of vegetation from aerial photographs and field inspections after the flood. It was observed that the simulated water level was roughly consistent with the trace water level, and from 14.5 KP to 16.5 KP, there was residual and wash-out vegetation affecting the water level during flooding. It is expected that vegetation flowed out before the flow peak, especially in the upper reaches where the wash-out of vegetation was remarkable in the analysis section.

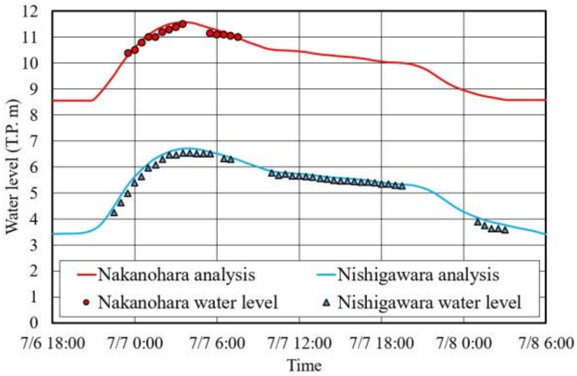

Figure 9. Comparison of simulated and observed water levels at Nakanohara and Nishigawara during flooding in July 2018.

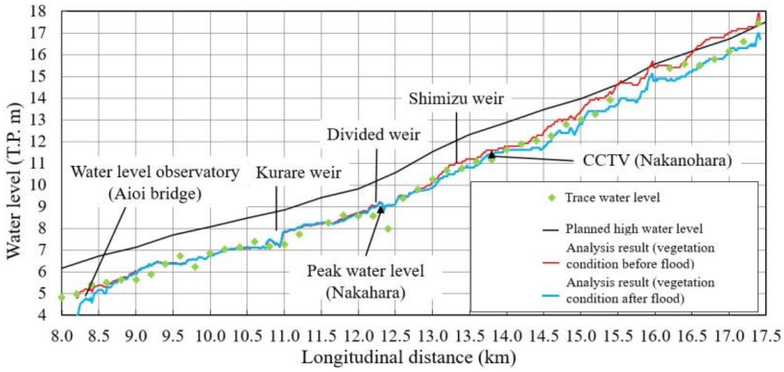

Figure 10. Longitudinal variation of water level at the peak flow rate in Asahi River (left bank).

4.2 Examination of residual and wash-out conditions of vegetation

4.2.1 Fluid force and vegetation wash-out during peak flow rate

Considering the effort of the field survey, the scope of the survey was limited from the 14.5 KP to 17.4 KP in the following study. In addition, the results of the field inspection and the vegetation data of ALB were compared with the 2 m grid, and the relationship between the wash-out condition of vegetation and the tractive force was examined for those for which the vegetation wash-out was clearly judged. In Figure 11, the existence rate of each vegetation species in the analysis grid (about 10 m width), which was used to determine the residual and wash-out of vegetation in Gion and Nakahara areas, was compared with the riverbed shear stress τ and moment M . In this case, the abundance rate was calculated from the data on the discrimination of the ground surface of 2 m mesh, and the data in the figure were calculated from the flood flow under the conditions of vegetation flourish before the flood, and calculated from the hydraulic amount at the peak flow rate. From the figure, it is observed that the abundance rate is roughly relevant, tends to flow out when τ and M become large, and it is easy to distinguish between residual and wash-out when relatively used, but there is no clear limit value that identifies both.

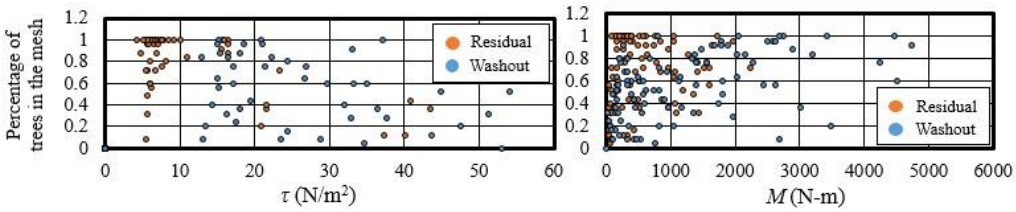

Figure 11 (a). The relationship between the proportion of trees and τ, M.

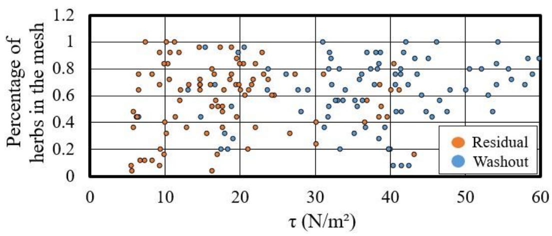

Figure 11 (b). The relationship between the proportion of herbs and τ.

In Figure 12, the limit conditions of residual and wash-out of trees and herbs were examined using the non-dimensional critical tractive force ratio τ_{*i}/τ_{*ic} at 85% particle size (Tanaka et al., 2009). The ratio value of any vegetation species is scattered quite a bit, and (1) the vegetation may remain even if the ratio is close to 2 beyond 1 (the state in which coarse gravel begins to move on the riverbed), and (2) the condition of vegetation may flow out even if it is considerably below 1. In addition, (3) the ratio can be considerably higher.

As an interpretation, (1-a) while vegetation flourish, riverbed gradient, and riverbed particle size are not uniform in terms of surface, the currently used analysis mesh and riverbed material survey are not enough to accurately reproduce the surrounding flow conditions and non-dimensional critical tractive force. (1-b) In response to the riverbed disturbance, it is thought that the strength to flood flow is increased by the resistance of the root and the ground of the high-length trees. In addition, (2) since the calculation is performed in the state before the wash-out even if it actually flows out in the previous analysis, for example, the tree in the gentle flow in the tree community is not reflected in the calculation even if the surrounding trees actually flow out and become water ingress. In addition, (3) in order to evaluate the ratio by the hydraulic quantity at the peak flow rate, it is considered that it was wash-out state by a large tractive force at the peak, apparently even if it flows out in the middle of the water level rise of the flood.

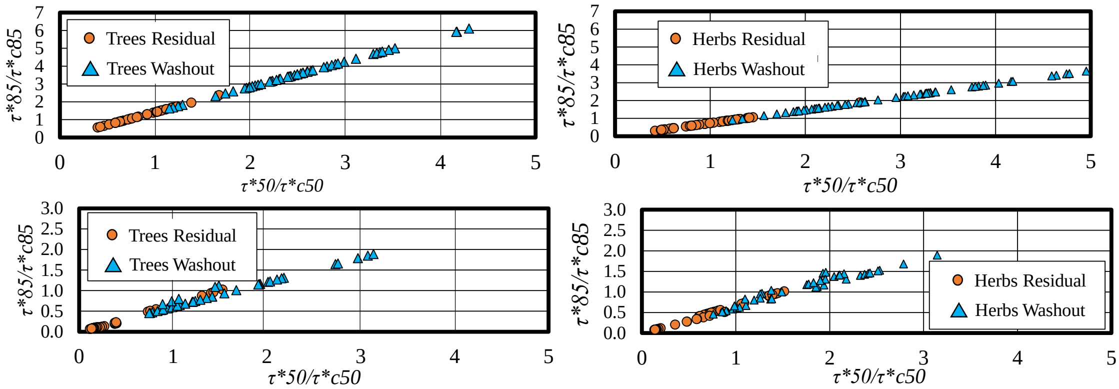

Figure 12. Variation of the non-dimensional tractive force by particle size (Top: Nakahara; Bottom: Gion).

4.2.2 *Flood flow analysis considering resistance change caused by vegetation wash-out*

At present, (1-a) is considered to be difficult to refine due to the relationship between measurement and calculation technology and labor. Therefore, in this study, the following simple model was considered for (1-b), (2) and (3), and the flood flow analysis was performed while conducting the wash-out process of vegetation as a flow field. From the past research (Komatsu and Yamamoto, 2009), it is observed that the lodging and wash-out of trees and herbs are basically caused by fluid strength acting and disturbance of the riverbed. Therefore, it is thought that the phenomenon can be arranged by using the non-dimensional critical tractive force ratio $\tau_{*_i}/\tau_{*_{ic}}$ and the moment ratio M/M_c roughly. Here, the limit moment M_c is thought to be related to the diameter at chest height of the vegetation, that is, the growth amount and the development of the roots. Moreover, it is thought that the limit condition of the residual and the wash-out of vegetation can be roughly arranged by $\tau_{*_i}/\tau_{*_{ic}}$ and the vegetation height when M is considered to increase with the water level rise of the flood as well as τ_{*_i}. Therefore, the model diagram of the limit condition for the residual and wash-out of vegetation, considering 85% particle size as a representative value, is shown in Figure 13. Case 0 is a past research method in which vegetation always remains (including the wash-out) regardless of flow condition or vegetation height, and Case 1 is a condition in which the limit of the wash-out is constant of 2 ($=\tau_{*_i}/\tau_{*_{ic}}$) regardless of vegetation height, and Case 2 changes the limit value gradually depending on the vegetation height. It was taken into consideration that the herbs were not dependent on vegetation height, and a certain value of 2 was imposed as a limit condition. In addition, the value of $\tau_{*_i}/\tau_{*_{ic}}$ is 2 as the reference value in this study because vegetation flows out whenever this value is exceeded.

The condition of vegetation species and ground covers based on the flood flow analysis as depicted in Figure 14. In Case 1, local reproducibility was observed to some extent compared with the situation of the Asahi River after the flooding, previously presented in Figure 6. However, at the N-1 and O-1 areas, it was observed that the vegetation flowed out excessively. Contrarily, at the O-2 area, it was noticed that the vegetation condition was almost no wash-out. Looking at these passages in detail, it can be mentioned that N-1 and O-1 areas were occupied by tall trees, while O-2 was dominated by short vegetation that easily flowed out. However, after verification of the vegetation data obtained from ALB and the actual wash-out situation, and the Case 2, which added the effect to the wash-out conditions at the peak of the flood comparing with Case 1, it was noticed that the result of the analysis was quite close to the remaining and wash-out situation in the local area. In addition, there was no difference in the analysis results considering the presence or absence of lodging of the young bamboo in the Tamagashi area, previously elucidated in Figure 7.

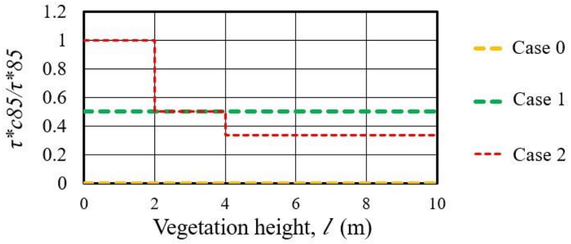

Figure 13. Model diagram of the limit condition for the residual and wash-out considering vegetation height.

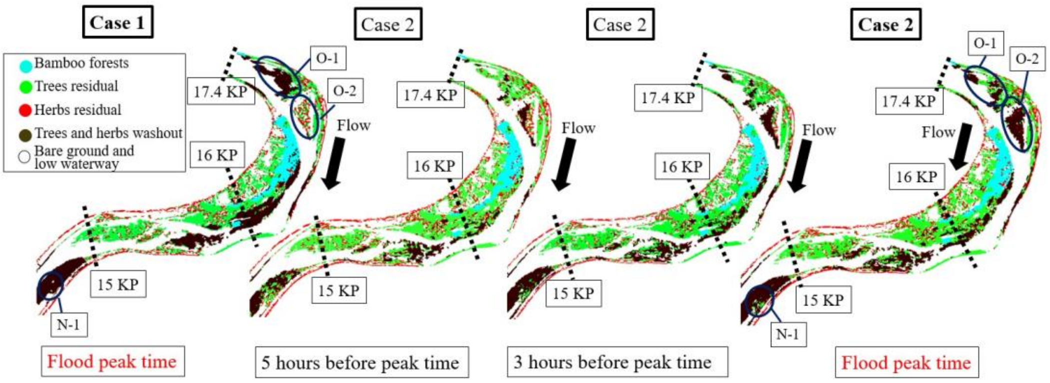

Figure 14. The condition of vegetation species and ground covers based on the flood flow analysis.

5. CONCLUSIONS

In this study, taking the 2018 Asahi River flood as an example, the local topography, ground cover, and vegetation conditions were reproduced with ALB data, and the residual and wash-out conditions of vegetation during the flooding were confirmed. In addition, although the relationship between the wash-out situation and the drag of vegetation at the peak of flood flow and the tractive force acting on the ground was considered, it was difficult to organize the limit conditions of vegetation wash-out. Therefore, a simple model was developed considering vegetation height in addition to the tractive force, and the flood flow analysis was performed taking into account the resistance reduction due to vegetation wash-out.

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