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Yagisawa, Junji; Tanaka, Norio

Evaluation of Removal Condition of Invasive Plant 'Eragrostis Curvula' by Considering Erosion Rate

EVALUATION OF REMOVAL CONDITION OF INVASIVE PLANT '*Eragrostis curvula*' BY CONSIDERING EROSION RATE

Junji Yagisawa[1] and Norio Tanaka[2]

[1] Graduate student, Graduate School of Science and Engineering, Saitama University
255 Shimo-okubo, Sakura-ku, Saitama 338-8570, Japan, e-mail: s06de007@mail.saitama-u.ac.jp
[2] Professor, Graduate School of Science and Engineering, Saitama University
255 Shimo-okubo, Sakura-ku, Saitama 338-8570, Japan, e-mail: tanaka01@mail.saitama-u.ac.jp

ABSTRACT

The removal condition of *Eragrostis curvula* vegetated on the gravel bed bar in the Arakawa River, Japan was evaluated by the depth of the substrate degradation, *E*, at the typhoon 9 event in 2007. The degradation depth (*E*) around the colonies of *E. curvula* was estimated by integrating the erosion rate as a function of the difference between the bed shear stress and the critical bed shear stress of d_{84} , $\tau_{c84,}$ around *E.curvula*, considering the flood duration in which the shear stress is larger than the τ_{c84}. ΔT, and the variation of the colony density. For removing *E.curvula* by a flood, the duration ΔT should be large enough so that the depth of the substrate degradation becomes larger than about 60% of the root penetrating depth. This Removal condition can apply to *E. curvula* at the fringe of the vegetated area; however, it cannot apply to the inside of the area. This study indicates the importance of evaluating the decrement of the velocity and the shear stress inside the vegetated area for estimating the whole removal condition of *E.curvula.*

Keywords: shear stress, non-dimensionalized shear stress, erosion rate, *Eragrostis curvula*

1. INTRODUCTION

Vegetations in rivers create a valuable natural environment that maintains the biodiversity. The decrease of a gravel bed bar by the colonization of monospecific or invasive plants has become one of the important problems in the midstream of Japanese rivers because such plants were reported to reduce not only the mobility of the gravel but also decrease the biodiversity in a river. *Eragrostis curvula*, one of the representative invasive plant in Japan, affects the biodiversity of a gravel bed bar (Matsumoto et al., 2000). It is listed up as a plant that needs to be controlled in Japan. *E. curvula* colonies provide large drag forces to the flow and increase the sediment deposition in their wake. They also change the threshold of the gravel movement in the vegetated zone. Then, the rehabilitation of the river gravel bed and the removal of the plant are discussed recently.

In previous researches, the removal condition of vegetations was evaluated mainly with four methods; 1) maximum permissible velocity (USDA (1954)), 2) equivalent stone size (Parsons (1963)), 3) permissible tractive force (Temple (1980)) and 4) relative height and permissible deflection (Samani and Kouwen (2002)). In some studies in Japan, the removal condition of grass type vegetation is evaluated by the non-dimensionalized shear stress or the shear stress. Suetsugi et al.(2004) evaluated the removal condition of some grass type vegetations at Tamagawa River and Chikuma River by using the non-dimensionalized shear stress of d_{50} (τ_{*50}), the representative grain diameters at which 50% volume are passed the sieve. However, they didn't include the influence of the vegetation density on the bed shear stress and the duration in which the shear stress around the vegetation is larger than the critical shear stress. This research evaluates the removal condition of *E. curvula* by the erosion of substrate under different conditions of the flood duration and the shear stress changed by the plant density.

2. FIELD INVESTIGATION AND ANALYSIS

2-1 Field investigation and the analysis of the habitat characteristics

Field investigation were conducted on the *E.curvula*-vegetated gravel bar at Atakawa-Ohashi (hereafter ARO: Figure 1(a)) and Kumagaya-Ohasi (KUO: Figure 1(b)) in the Arakawa River, Japan. The colony diameter (D_c), density(M), shoot height (h_v) and the root anchoring depth (R_L as shown in Figure 2) of *E.curvula* were observed at the sites. The *E.curvula* characteristics were also observed at Inagi on the floodplain in the Tamagawa River, Japan. The distribution of grain sizes were measured arout the colonies. The coloring stones were set before the flood season at AR1-AR5 in Figure 1(a) for the measurement of the scour depth at a flood event.

The relative height difference from ordinary water level at the habitat in Arakawa-Ohashi(ARO), R_H, are calculated by the cross-sectional data and the daily discharge data at Kumagaya discharge station from 1972 to 2001.

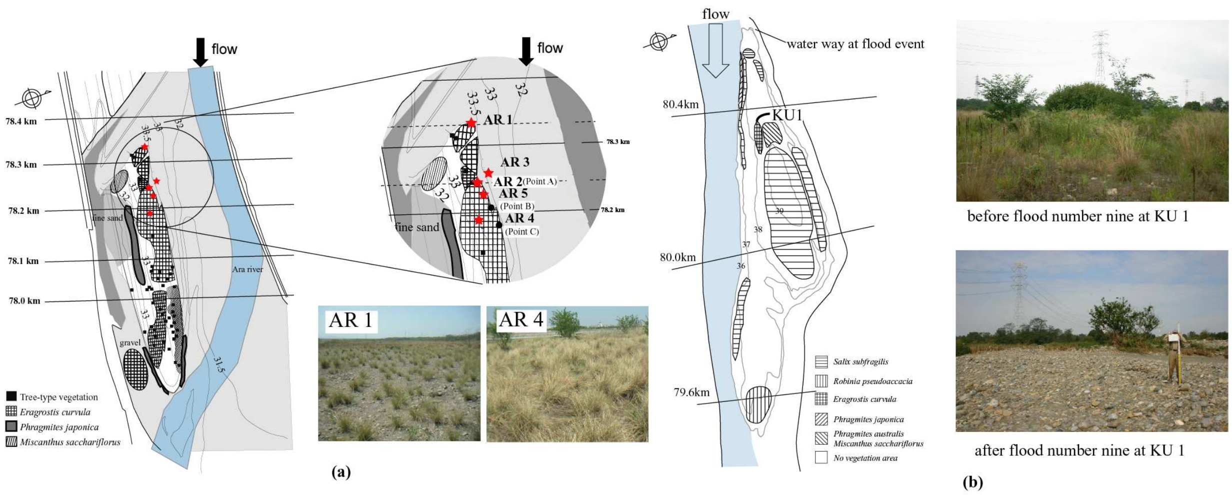

Figure 1 The observed habitat location and the vegetation map at,
(a) Arakawa-Ohashi (ARO)
(b) Kumagaya-Ohashi (KUO)

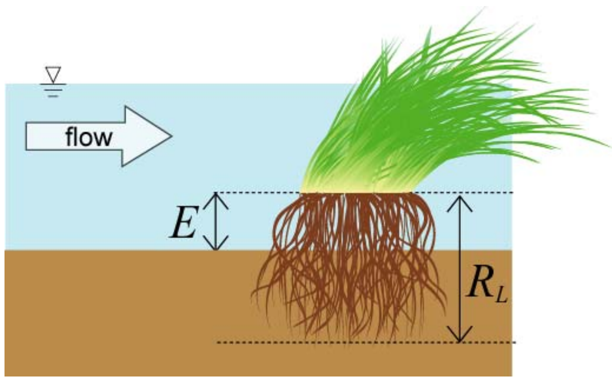

Figure 2 Definitions of the E and R_L
E : The depth of substrate degradation by the flood
R_L : Root penetrating depth

2-2 Analysis of the depth of substrate degradation around *E. curvula*.

The depth of substrate degradation by a flood, E (m), was evaluated using the equation by Samani & Kouwen(2002) as,

$$E = \int_{t_1}^{t_2} E_r dt = \int_{t_1}^{t_2} A(\tau_e - \tau_{c84})^B dt \qquad (1)$$

where, E_r (m/s) is the erosion rate, τ_e is the shear stress considering the colony diameter and plant density of *E. curvula* (N/m^2), τ_{c84} is the critical shear stress of d_{84} (grain size for which 84 % of the material weight is finer) around colony (N/m^2), A is the erosion rate coefficient, B is the erosion rate exponent (=1 in this study), τ_{c84} was calculated by the Egiazaroff equation (Egiazaroff, 1965), t_1 and t_2 are the time range in which τ_e is larger than τ_{c84}. The erosion rate coefficient A was estimated as 5.2×10^{-8} by the observed bed degradation depth at *E. curvula* vegetated area (AR4) in Figure 1(a) at Arakawa-Ohashi in Arakawa River for the Typhoon 9 flood in 2007 and this value was applied to other sites. τ_e was calculated using the drag characteristics and vegetation condition (Table 1) of the plant by Eq. (2) (Yagisawa & Tanaka, 2007).

$$\rho u_*^2 A_{r-wo} + \frac{1}{2}\rho u^2 C_d A_r M = \rho g h I_e - \rho g h_v I_e \pi M (1-\lambda)(D_c/2)^2 \qquad (2)$$

where, ρ (kg/m^3) is the fluid density, A_{r-wo} (m^2) is the area of the bed without plants, h (m) is the water depth, M (number of colonies / m^2) is the density of the colonies, I_e is the energy gradient, u_* (m/s) is the friction velocity, λ is the porosity of a colony, u (m/s) is the velocity, C_d is the drag coefficient of the colony, g (m/s^2) is the gravitational acceleration and A_r (m^2) is frontal projected area of the colony.

The drag coefficient C_d was set by the experimental formula including the effect of the relative height (H/h_v) (Tanaka et al., 2008). u, h and I_e were estimated using the result of 2-D unsteady flow model with a generalized coordinate system explained in the next section.

Table 1 Characteristics of *E. curvula* and the substrate condition at the each site

Location		Density M (colonies/m^2)	Reference diameter of a colony D_c (m)	Shoot height h_v (m)	Particle diameter (cm) d_{50} ☆	d_{84} ☆
Arakawa-Ohasi	AR 1	0.52	0.23	0.85	0.03	0.05
	AR 2	1.76	0.20	0.79	0.03	0.05
	AR 4	2.44	0.29	0.97	0.03	0.05
	AR 5	2.40	0.21	0.83	0.03	0.05
Kumagaya-Ohasi	KU 1	2.47	0.13	0.64	0.04	0.07

☆ d_{50} and d_{84} are values of grain sizes for which 50% and 84% of the material weight is finer, respectively.

2-3 River flow analysis

River flow was analyzed by a continuity equation (Eq. (3)) and a two-dimensional depth-averaged Reynolds equation (Eqs. (4) and (5))). The porosity inside the vegetative area was considered in the continuity equation, the drag force due to vegetation was also included in the momentum equation (Takemura and Tanaka, 2005). These equations are

$$\theta \frac{\partial}{\partial t}\left(\frac{h}{J}\right) + \frac{\partial}{\partial \xi}\left(\frac{Uh}{J}\right) + \frac{\partial}{\partial \eta}\left(\frac{Vh}{J}\right) = 0 \qquad (3)$$

$$\frac{\partial}{\partial t}\left(\frac{q_x}{J}\right)+\frac{\partial}{\partial \xi}\left(\frac{Uq_x}{J}\right)+\frac{\partial}{\partial \eta}\left(\frac{Vq_x}{J}\right)=-gh\left(\frac{\xi_x}{J}\frac{\partial Z_s}{\partial \xi}+\frac{\eta_x}{J}\frac{\partial Z_s}{\partial \eta}\right)-\frac{\tau_x}{\rho J}-\frac{f_x}{\rho J}+\frac{\xi_x}{J}\frac{\partial}{\partial \xi}\left(-\overline{u'^2}h\right)+\frac{\xi_y}{J}\frac{\partial}{\partial \xi}\left(-\overline{u'v'}h\right)+\frac{\eta_x}{J}\frac{\partial}{\partial \eta}\left(-\overline{u'^2}h\right)+\frac{\eta_y}{J}\frac{\partial}{\partial \eta}\left(-\overline{u'v'}h\right) \quad (4)$$

$$\frac{\partial}{\partial t}\left(\frac{q_y}{J}\right)+\frac{\partial}{\partial \xi}\left(\frac{Uq_y}{J}\right)+\frac{\partial}{\partial \eta}\left(\frac{Vq_y}{J}\right)=-gh\left(\frac{\xi_y}{J}\frac{\partial Z_s}{\partial \xi}+\frac{\eta_y}{J}\frac{\partial Z_s}{\partial \eta}\right)-\frac{\tau_y}{\rho J}-\frac{f_y}{\rho J}+\frac{\xi_x}{J}\frac{\partial}{\partial \xi}\left(-\overline{u'v'}h\right)+\frac{\xi_y}{J}\frac{\partial}{\partial \xi}\left(-\overline{v'^2}h\right)+\frac{\eta_x}{J}\frac{\partial}{\partial \eta}\left(-\overline{u'v'}h\right)+\frac{\eta_y}{J}\frac{\partial}{\partial \eta}\left(-\overline{v'^2}h\right) \quad (5)$$

where θ is the porosity, t is the time, J is the Jacobian, (u, v) is the depth-averaged velocity in x, y direction (m/s), respectively, (U, V) is the contravariant velocity component of (u, v), (q_x, q_y) is the discharge flux(m^2/s), Z_s is the water level (m), (τ_x, τ_y) is the shear stress in x, y direction (N/m^2), respectively, $-\overline{u'^2}$, $-\overline{u'v'}$, $-\overline{v'^2}$ is the depth-averaged Reynolds stress (m^2/s^2), (f_x, f_y) is the drag force per unit area in x, y direction (N/m^2), respectively. To analyze the drag force f_x and f_y including the tree stand structure as

$$f_x = \frac{1}{2}m\rho C_{d-ref} d_{BH} u\sqrt{u^2+v^2}\int_0^h \frac{d(z)}{d_{BH}}\frac{C_d(z)}{C_{d-ref}}dz \quad (6)$$

$$f_y = \frac{1}{2}m\rho C_{d-ref} d_{BH} v\sqrt{u^2+v^2}\int_0^h \frac{d(z)}{d_{BH}}\frac{C_d(z)}{C_{d-ref}}dz \quad (7)$$

$$\alpha(z)=\frac{d(z)}{d_{BH}} \quad , \quad \beta(z)=\frac{C_d(z)}{C_{d-ref}} \quad (8)$$

where, z is the vertical axis from ground (m), m is the density of trees per unit area (Number of trees/m^2), $C_d(z)$, $d(z)$ is the drag coefficient, cumulative width of tree trunks and branches (m) at height z, respectively, C_{d-ref} is the reference drag coefficient (=1.0 considering a circular cylinder in this study), d_{BH} is the trunk diameter at breast height (=1.3 m from ground), $\alpha(z)$ is the additional coefficient for expressing the vertical tree structure, $\beta(z)$ is the additional coefficient for representing the effect of leaves(=1.25 considering Fukuoka and Fujita(1990)). For more details, see Tanaka et al.(2007).

River flow analysis was applied between 76 km and 82 km from river mouth of Arakawa River. The observed discharge at Uematsubashi gauge station and the observed water level at Kumagaya gauge station were used as the boundary condition. The grid sizes of cross-stream and streamwise direction were set about 8 m, 50 m, respectively. The surface elevation data was averaged and set in each grid. Manning roughness coefficient, n ($m^{-1/3}s$), was given as 0.035 in this study. The model was validated by comparing the flood water marks at the Typhoon 9 event in 2007.

2-4 Critical shear stress estimation for d_{50} and d_{84}

For evaluating the shear stress acting on the grain, τ_{*i}, the non-dimensionalized shields parameter that usually used considering 'the gravity force (slope direction)' over 'the weight of the grain in water' as below:

$$\tau_{*i}=\frac{\rho g h I_b}{(\rho_s-\rho)g d_i}=\frac{h I_b}{\left(\frac{\rho_s}{\rho}-1\right)d_i} \quad (9)$$

where, ρ_s is the density of the particle, d_i is the grain diameter at which i % volume is passed the sieve and I_b is the bed slope. The critical shear stress of d_{50} for the initiation of motion, τ_{*c50} can be approximated from the Shields diagram as:

$$\frac{\tau_{*c50}}{(\rho_s - \rho) g d_{50}} = 0.06 \tag{10}$$

For calculating the effects of the grain size distribution, critical shear stress of each grain size *i*, τ_{*ci} , was proposed by Egiazaroff(1965) as:

$$\frac{\tau_{*ci}}{(\rho_s - \rho) g d_i} = \frac{0.1}{[\log_{10} 19(d_i / d_m)]^2} \tag{11}$$

where, d_m is the medium grain size. τ_{*50} , τ_{*84} is derived by substituting $d_i = d_{50}$ or d_{84} into Eq.(9), respectively. τ_{*c84} is derived by substituting $d_i = d_{84}$ into Eq.(11).

3. RESULTS AND DISCUSSIONS

3-1 Analysis of washing out of *E. curvula* in the other river by the removal condition in the previous research

The relationship between τ_{*50}/τ_{*c50} and τ_{*84}/τ_{*c84} is shown in Figure 3. The values of τ_{*50}/τ_{*c50} and τ_{*84}/τ_{*c84} are calculated for Arakawa River(AR), Tamagawa River(TM), Asahi River(AS: data are from Sanada et al.(2006)), Yasugawa River(YS: data are from Foundation for Riverfront Improvement and Restoration (not published)) and Yoshinogawa River(YO: data are from Ministry of Land, Infrastructure and Transport(MLIT), 2004). Closed plots(WO) or open plots(NWO) show whether *E. curvula* colonies were washed out by flood or not, respectively. Suetsugi et al.(2004) reported that *E. curvula* colonies can be washed out if the value of τ_{*50} is larger than 0.09 to 0.11. Line A or Line B shows the value that τ_{*50}/τ_{*c50} is equal to 0.09 or 0.11, respectively. According to the definition of Suetsugi et al.(2004), *E. curvula* should be washed out by flood when the value of τ_{*50}/τ_{*c50} exceeds Line B, and *E. curvula* should not be washed out when the value of τ_{*50}/τ_{*c50} is less than Line A. However, some *E.curvula* colonies were not washed out even when τ_{*50}/τ_{*c50} exceeded Line B. In

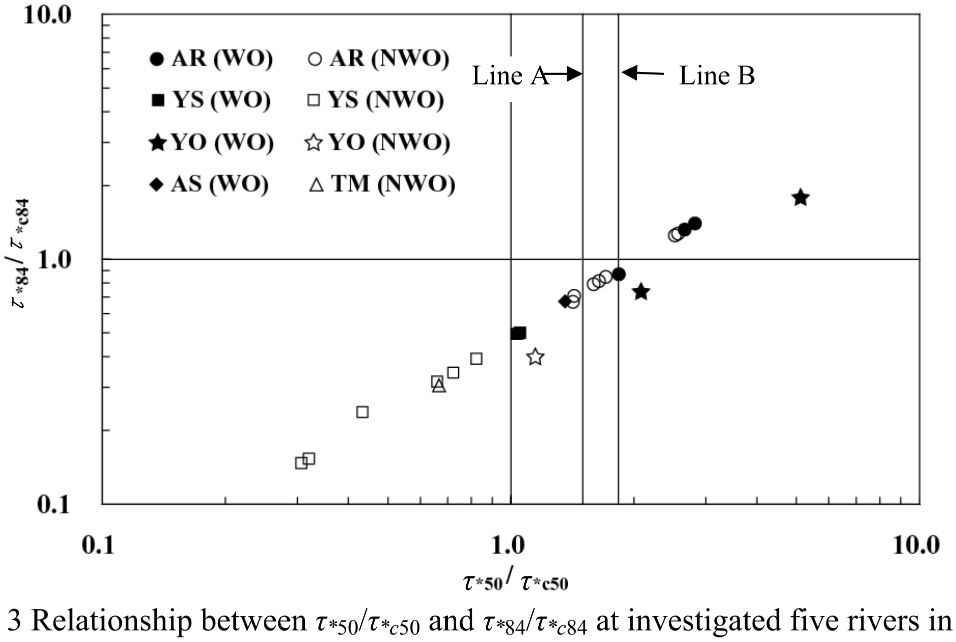

Figure 3 Relationship between τ_{*50}/τ_{*c50} and τ_{*84}/τ_{*c84} at investigated five rivers in Japan. Arakawa River(AR), Tamagawa River(TM), Asahikawa River(AS), Yasugawa River(YS) and Yoshinogawa River(YO). Open plots : not washed out (NWO), closed plots : washed out (WO)

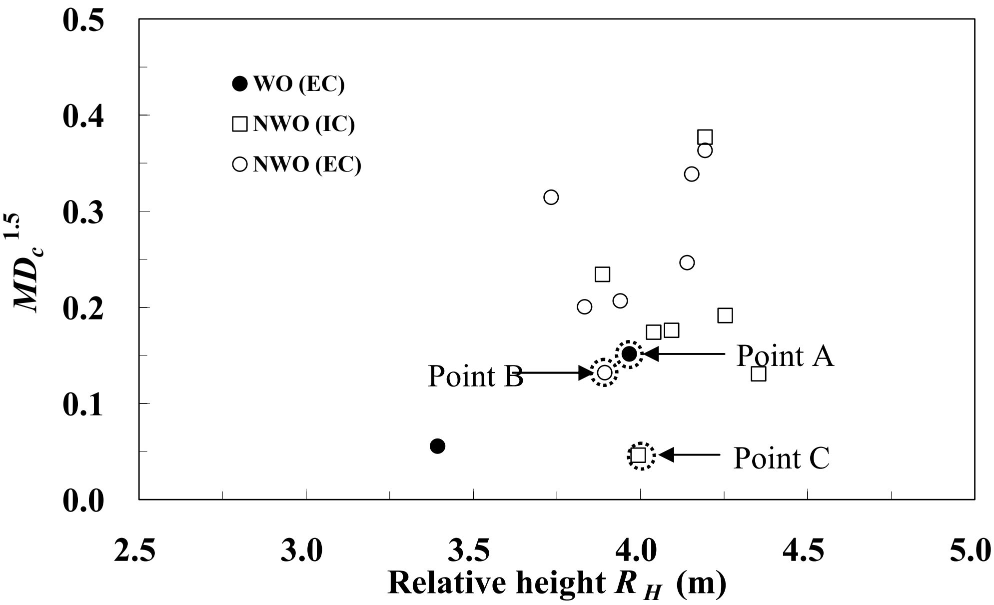

Figure 4 Relationship between R_H, and $MD_c^{1.5}$
R_H : the relative height difference from ordinary water level at Arakawa-Ohashi,
$MD_c^{1.5}$: the parameter which expresses the magnitude of the drag force by *E. curvula*.
EC : the fringe of the vegetation of *E. curvula*, IC : inside the vegetation of *E. curvula*.

addition, some *E. curvula* colonies were washed out even when τ_{*50}/τ_{*c50} was less than Line A. These results indicate that the removal condition of *E.curvula* cannot be decided by using only τ_{*50}. For elucidating the removal condition, it is important to consider not only the shear stress but also the flood duration, vegetation density and the colony size of *E. curvula*.

Figure 4 shows relationship between the relative height difference from ordinary water level at Arakawa-Ohashi(ARO), R_H, defined in section 2-1, and a parameter $MD_c^{1.5}$, that express the magnitude of drag forces by plant (Yagisawa & Tanaka, 2007). Closed and open plots show the washed-out colonies at the fringe of *E. curvula* vegetation and the unwashed-out colonies at inside *E. curvula* vegetation, respectively. The R_H of Point A is larger than the R_H of Point B and Point C. This means that Point A is rather difficult to be affected by the flood disturbance compared with Point B and Point C. In addition, the $MD_c^{1.5}$ of Point A is larger than that of Point B and Point C. This means that the shear stress of Point A is smaller than that of Point B and Point C. However, the plant at Point A was washed out in spite of the condition that was hard to be washed out than Point B and Point C. These colonies vegetated on the same gravel bed bar and the distance among each habitat was about 10 - 20 m (Figure 1(a)). The τ_{*50} of these colonies should be almost the same because the water depth at these colonies is not different. Therefore, the removal condition by Suetsugi et al.(2004) cannot apply to *E. curvula* colonies at ARO in Arakawa River.

3-2 Evaluation of the removal condition of *E. curvula* by considering the depth of substrate degradation

Figure 5 shows the time series of shear stress with *E. curvula* vegetation, τ_e, and without the plant, τ which were calculated by Eq.(2) at ARO and KUO in Arakawa River. The critical shear stress τ_{c84} are also included in the figure. The values of τ_e at each vegetated location were smaller than the values of τ (dashed line). In Figure 5(a), the values of τ_e become larger with smaller M and D_c . ΔT is long when the time series of τ_e are large, where, ΔT is the duration in which shear stress around vegetation was larger than the critical shear stress, τ_{c84}.

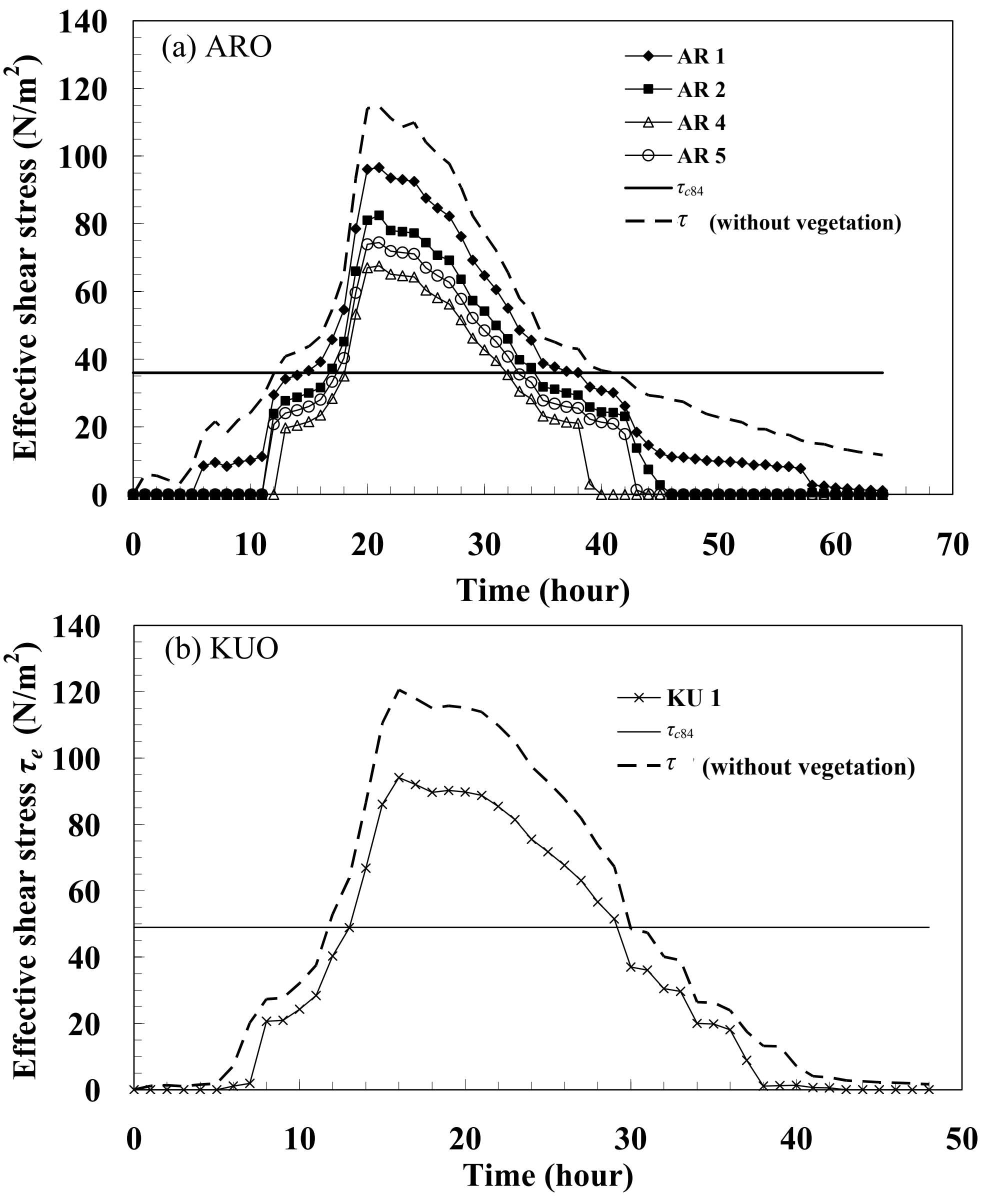

Fig.5 Time variation of the effective shear stress around colony at each observation site
(a) Arakawa-Ohashi (ARO), (b) Kumagaya-Ohashi (KUO)
(open plots : remained after flood, closed and × symbol : removed by flood)

ΔT affects the depth of the substrate degradation, E.

The relationship between E and the root penetrating depth, R_L at ARO (fringe region of *E.curvula* vegetated area: AR1,and AR2) is shown in Figure 6. Closed and open circles show whether *E. curvula* colonies were washed out by flood or not, respectively. The ΔT should be large enough that E exceeds about 60 % of R_L for removing this plant. Hereafter, we define the 60 % value as 'the threshold line for removing *E.curvula*'.

Figure 7 shows the relationship between ΔT and non-dimensional bed degradation depth, E/R_L. The solid line in Figure 7 is 'the threshold line for removing *E.curvula*'. This removal condition was decided by using R_L and E at the upstream fringe of the vegetated area (1 m in streamwise and 5 m in cross-stream direction) on the bar in ARO site. Point A, Point B or Point C in Figure 7 corresponds to Point A, Point B or Point C in Figure 4, respectively. This

figure expresses well the washed out situation at the flood event, especially for point A

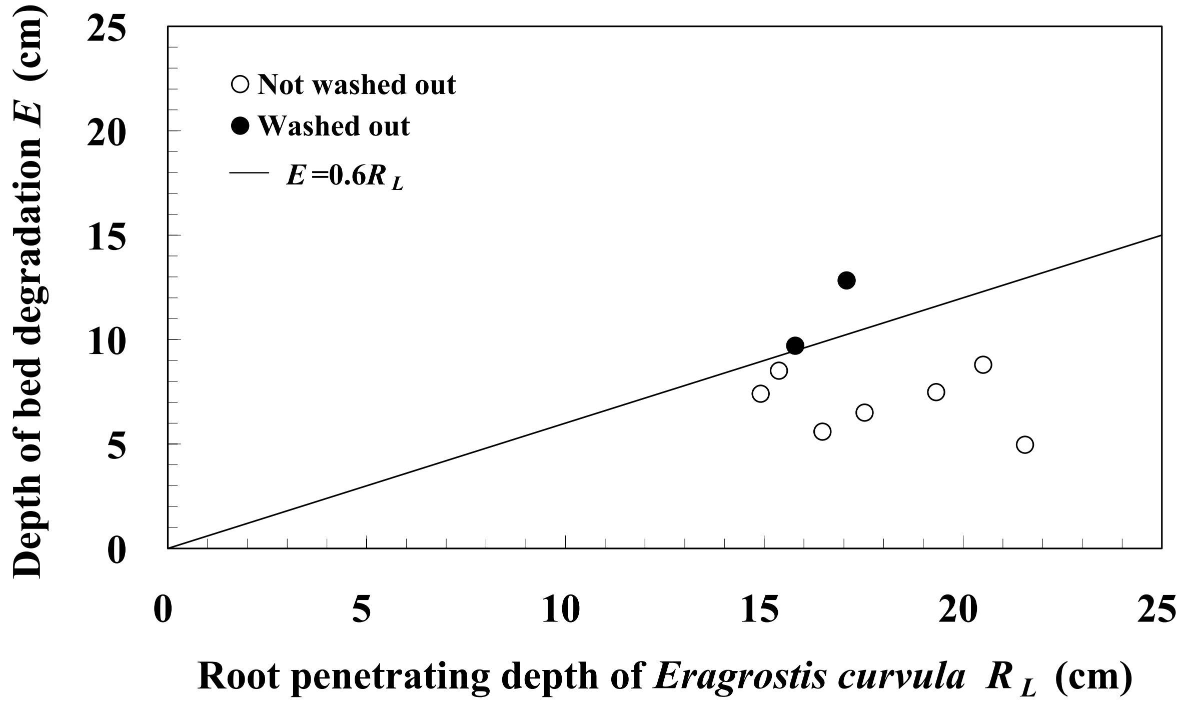

Fig.6 Relationship between root penetrating depth, R_L, and the depth of bed degradation, E, at Arakawa-Ohashi. (open circles : remained after flood, closed circles : removed by flood)

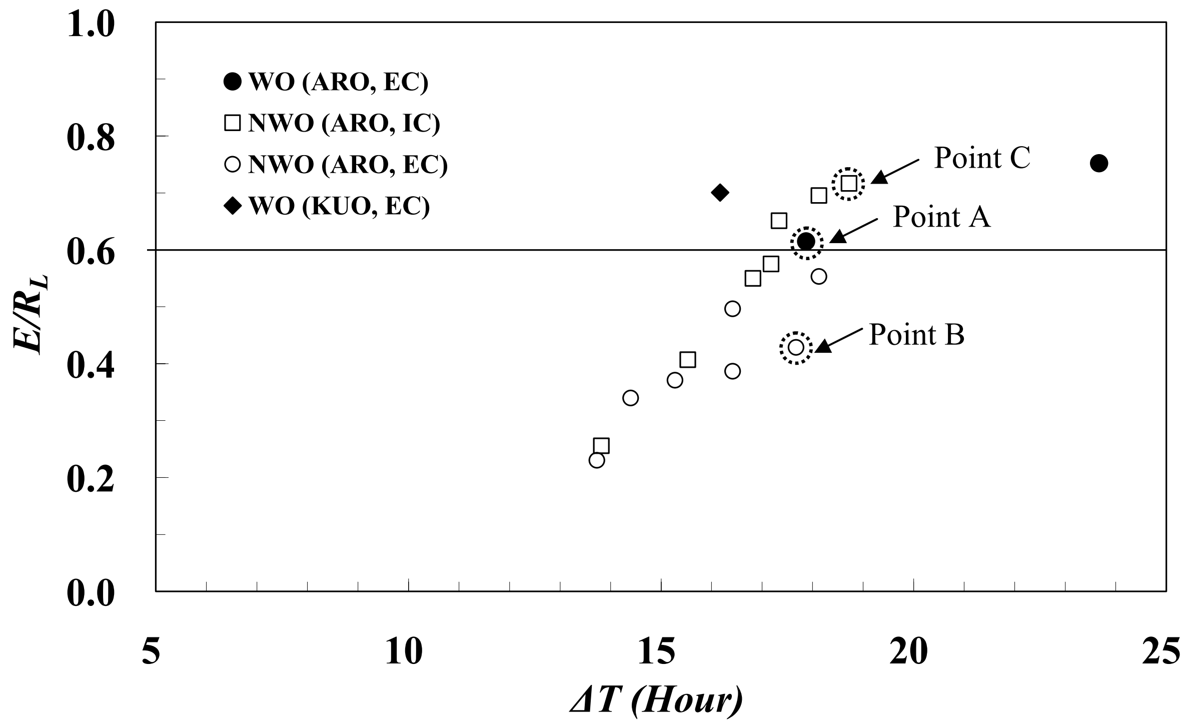

Fig.7 Relationship between ΔT and E/R_L.

ΔT is the duration in which shear stress around vegetation was larger than the critical shear stress of d_{84}. E/R_L is defined as non-dimensional bed degradation depth

open Points : remain after flood, closed Points : removal by flood

ARO : Arakawa-Ohashi, KUO : Kumagawa-Ohashi and B. ΔT of Point A and Point B was 17.9 and 17.7 hours, respectively. In addition, E of Point A and Point B was 9.6 and 8.8 cm, respectively. These values of Point B are not so different from the values of Point A. However, the root penetrating depths of *E. curvula* were different between Point A(=15.8 cm) and Point B(20.5 cm) because of the difference of the colony size. Even if the E of Point B is at the same level of that at Point A, the washed out condition is found to be different. Therefore, this analysis could represent why the plant at Point A is washed out and Point B is not washed.

The same method was applied to another habitat at the fringe of *E.curvula* vegetation area in KUO in Arakawa River. The value of E/R_L (closed diamond plot in Figure 7) exceeded 'the threshold line for removing *E.curvula*'. The colony at the fringe of *E.curvula* vegetation satisfies the removal condition at KUO. However, the removal condition of *E. curvula* could not apply to the colonies inside the vegetated region at ARO. This is because the decrement of velocity and shear stress inside colonies were not considered in this research.

4. CONCLUSION

The removal condition of *E. curvula* was evaluated by the depth of the substrate degradation E, and the duration in which the shear stress is larger than the critical shear stress of d_{84} around *E. curvula*, ΔT. The ΔT should be large enough so that E becomes larger than about 60 % of R_L, root penetrating depth for removing this plant. This Removal condition can apply to *E. curvula* colonies at the fringe of the vegetated area; however, it can not apply to the plant inside the vegetated area. This study indicates the importance of estimating the decrement of the velocity and the shear stress inside the vegetated area for evaluating the overall removal condition of *E.curvula.*

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