

Application of Population Dynamics Modeling to Habitat Evaluation

– *Growth of Some Species of Attached Algae and Its Detachment by Transported Sediment* –

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Abstract. – Mathematical population dynamics modelling has been employed to simulate and predict habitat situation of living species. It is introduced to description of botanical growth in aquatic ecosystem by setting the growth and decay rate. Although the PHABSIM technique also can discuss habitat situation, it cannot evaluate the habitat with dynamical changes efficiently. Population dynamics is applied for developing habitat evaluation method in the paper. By investigating the algal habitat in the middle reach of the Yahagi River, the net growth rate is changed spatially corresponding to velocity and water-depth. According to the field observation and conventional hydraulic modeling, the growth rate and the detachment rate of attached algae is estimated. By applying the simulation, population dynamics modeling can be identified as one of the necessary angles for habitat evaluation.

Key words. – Population dynamics modelling, attached algae, algal habitat, growth rate, detachment rate, Yahagi River

INTRODUCTION

The study on the river ecosystem provides the understanding of the suitability of the situation of each area as habitat for each species. The PHABSIM (Physical Habitat Simulation, Bovee 1982; Stalnaker *et al.*

1995) is often performed where the investigated area as habitat is measured by physical properties such as velocity, water-depth and the composition of bed materials. This methodology was developed initially for predicting suitability of fish habitat condition. Although this conventional

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model guarantees the suitable area, but we often experience that the population or biomass in the place with the highest habitat suitability does not necessarily show the highest value, particularly, investigated when the species having low mobility is targeted.

Recently, the population dynamics (Teramoto 1996) is one of the attractive researches of ecology. It has been employed to simulate the development of living species by using mathematical models. When the population dynamic model is applied, the growth and decay rate of target species are investigated. The most important characteristic of this model is that it can describe temporal change in the habitat situation. Consequently, we can discuss inhabitant condition of organisms despite of their mobility. However, there is an ambiguity related to the selection of objective spatial scale in this model. In other words, the population dynamics have not been discussed by environmental change.

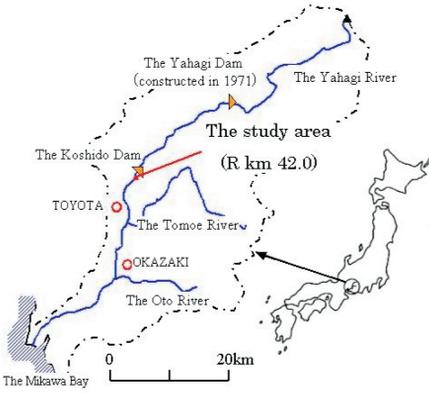
In the present study, an attempt was done to combine a habitat suitability evaluation with a population dynamics model that describes response of organisms. From the viewpoint of river ecosystem conservation, it is important to grasp dynamic condition of growing attached algae adequately because it feeds the other species in river. Therefore, by discussing about the dynamics of algal growth and the habitat suitability of algae in the middle reach of the Yahagi River, we can identify the the-

ory of population dynamics as one of the essential viewpoints for habitat evaluation. Firstly, field-data investigation has been conducted in the middle reach of the Yahagi River to estimate the growth rate and the environmental capacity of algae ash-free weight. Then, with the use of the field-observation data, the growth-detachment dynamics model for algae has been carried out. The simulation has demonstrated that the nuisance growth of algae is caused by the shortage of sediment transport.

FIELD INVESTIGATION IN THE YAHAGI RIVER

Study area

The main stem of the Yahagi River has a length of 117 km, and a catchment area of 1,830 km² in the central area of Japan. Seven dams in the main stem have been constructed, and the Yahagi Dam (river km (Rkm) 80.0; Figure 1) is the largest one. However, all of the dams but the Yahagi Dam are not sufficient enough to control discharges during strong flood events. Though the middle reach of the Yahagi River was a sand river before constructing the dams, it displays the characteristics of a cobble river at present (picture in Figure 1). The change has been produced by shortage of sediment supply from the upper reach due to the dams, it also have caused ecosystem degeneration such as blooming of attached algae (Tashiro *et al.*



The flow condition in the study area

Fig. 1. – Study area location in the Yahagi River

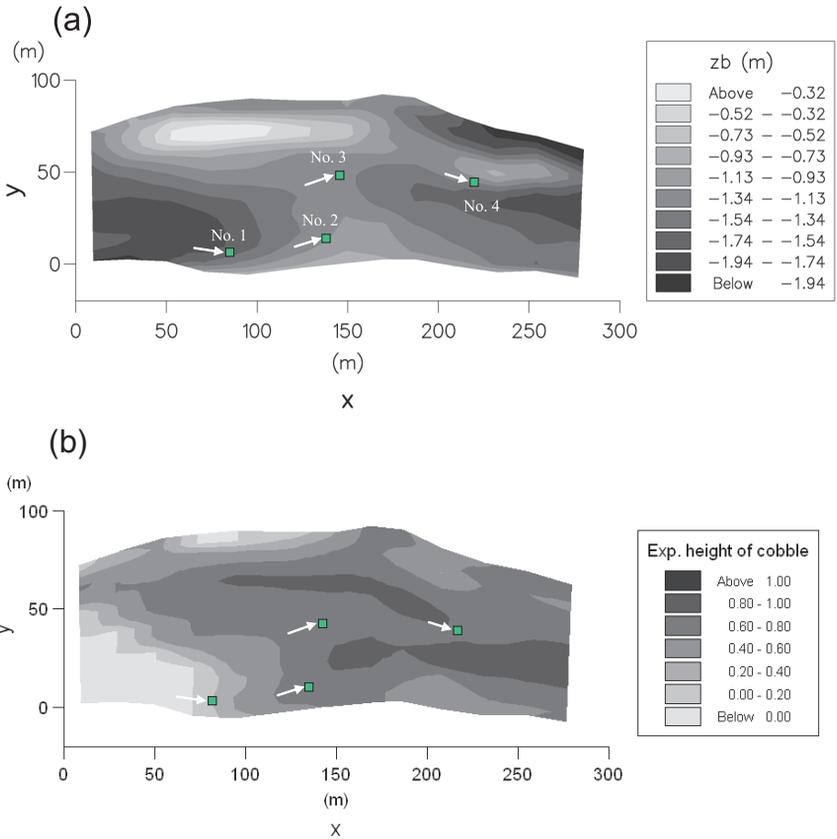


Fig. 2. – (a) Bed elevation contour and (b) Distribution of exposure height of substratum cobble, where No.1 to 4 provide the different bed type to investigate

2003). The study area showed the typical situation of the ecosystem degeneration, which located in the middle reach of the river, in Toyota City (Rkm 42.0; Figure 1).

Collection and analysis data

The investigated channel was defined to include one of the reaches and to include continuous sets of riffle and pool. A GPS (Global Positioning System) receiver and the levelling were used for the investigations. Figure 2 shows the contour of relative bed elevations and the distribution of exposure height of the substratum cobbles (Tashiro *et al.* 2003). Riverbed type is distributed in the channel with the pool section in the upper region and riffle section in the lower region. According to the change in riverbed type, the points were set as four quadrates (each 1m²) in Figure 2a to investigate algal habitat conditions. Riverbed type of No.1 to No.4 can be described as follows: pool section, transition section between pool and riffle, riffle section and rapid section, respectively.

The biomass fluctuation of attached algae in each quadrate was examined for about half of a year. Hydraulic conditions in each quadrate and water quality were also investigated. Figure 3 shows the change in ash-free weight and chlorophyll-a, which implies the biomass of attached algae on cobbles of each quadrate. The each plot means the

average value of 2 samples in the figure. Table 1 shows the result of water quality measurements during the investigation period. The parameters of attached algae biomass had the same trends for the 4 quadrates which started to increase from the fall season (September 2002) and exhibited the maximum value in the winter season (November or December 2002). The trends also correspond well to the previous study in a different location of the Yahagi River (Rkm 53.0, Uchida 1997). These common characteristics depend on low frequency of disturbance during the algal growth phase. Furthermore, the community dynamics of attached algae in the investigated reach suggested to be related to the change in water temperature.

Table 1. – Results of water quality measurement in the channel.

Date (yy/mm/dd)	Water temp. (°C)	Turbidity (NTU)
2002/7/23	24.6	37
2002/8/9	26.8	13
2002/8/30	27.4	3
2002/9/13	25.1	4
2002/9/26	21.3	5
2002/10/16	20.0	13
2002/10/30	15.1	5
2002/11/13	13.1	4
2002/11/28	11.6	37
2002/12/18	6.7	32
2002/12/30	6.1	42
2003/1/15	4.8	17

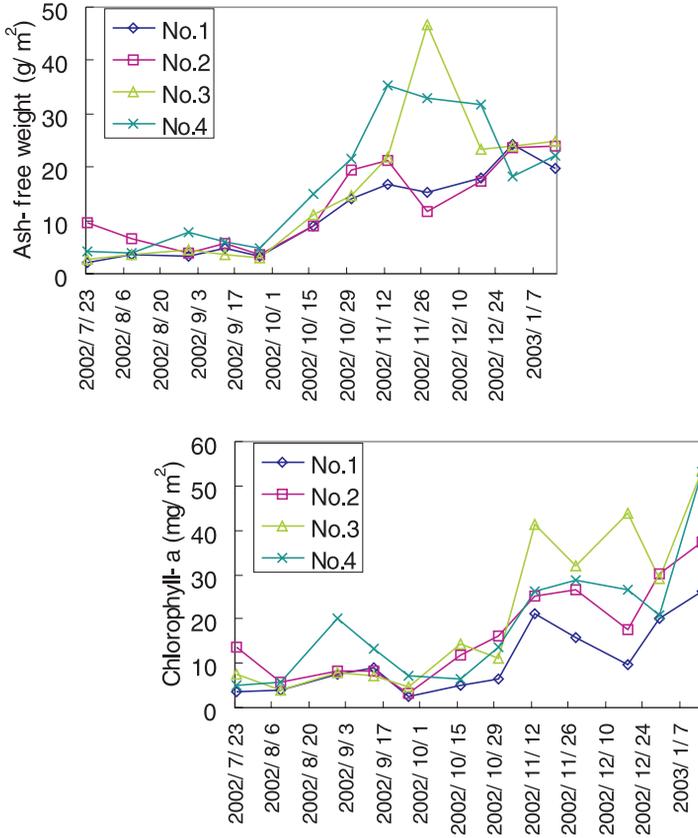


Fig. 3. – Ash-free weight (g/m²) (upper figure) and Chlorophyll-a (mg/m²) (lower figure) of attached algae on the cobble in each quadrate

MODELLING OF GROWTH-DETACHMENT DYNAMICS OF ATTACHED ALGAE

Model concepts

Logistic Equation can be utilized in order to explain population dynamics of organisms (Verhulst 1838). In this modelling of growth-detachment dy-

namics of attached algae, the effect of algal detachment is added to the conventional Logistic Equation as follows:

$$\frac{d}{dt} N(t) = \varepsilon \left(1 - \frac{N(t)}{K} \right) N(t) - pN(t) \quad (1)$$

where $N(t)$ denotes ash-free weight (g/m²); ε / p represent growth / detachment rate (day⁻¹) and K means environmental capacity.

Integrating Eq.(1) and giving N_0 as an initial ash-free weight, the following equation is derived.

$$N(t) = \frac{N_0 K(\varepsilon - \rho)}{\varepsilon N_0 + \{K(\varepsilon - \rho) - \varepsilon N_0\} \exp\{-(\varepsilon - \rho)t\}} \quad (2)$$

Furthermore, this equation is turned into discrete type for the simulation of growth-detachment dynamics of attached algae as follows:

$$N_{j+1} = \frac{N_j K(\varepsilon - \rho)}{\varepsilon N_j + \{K(\varepsilon - \rho) - \varepsilon N_j\} \exp\{-(\varepsilon - \rho)\Delta t\}} \quad (3)$$

in which the subscript j is the variable at the time step j ; Δt denotes time interval.

Estimation of growth rate and environmental capacity of attached algae

In this study, growth rate and environmental capacity of attached algae are estimated by using the field investigation. The following assumptions are employed to support the estimation:

- (1) Growth phase of attached algae started on 2002/9/26 ($t=0$) (Figure 3);
- (2) Cobbles of each quadrat have the same initial ash-free weight of attached algae (Figure 3);
- (3) The maximum ash-free weight of attached algae can be varied on cobbles of each quadrat as well as the environmental capacity;

(4) Detachment rate of attached algae is amount to be neglected during the growth phase because the growth rate is dominant the detachment rate in low disturbance condition;

(5) Nutrient concentration in the investigated reach is stable during the growth phase.

In the assumption (2), the common initial ash-free weight in the each quadrat is assumed 3.62g/m² which is the averaged value of the 4 quadrats on 2002/9/26 (Figure 3). The environmental capacity of the each quadrat in the assumption (3) is as follows: No. 1 = 24.1g/m²; No. 2 = 24.1g/m²; No. 3 = 46.8g/m²; and No. 4 = 35.4g/m². Under these assumptions, the conventional Logistic Equation (Verhulst 1838) is utilized. Figure 4 shows fitted Logistic Curves to each observed datum in the each quadrat (No. 1 ~ 4) for the estimation of growth rate and environmental capacity of attached algae community on cobbles in the each quadrat.

Generally, the algal blooming depends on nutrient condition and light environment. The effect of nutrient condition should be divided into nutrient concentration and supply rate in water (Borchardt 1996). Nutrient supply rate is often more important for growth of attached algae, and the velocity is related to the nutrient supply in the current water (Peterson 1996; Stevenson 1996). It is also known that light exploitation of attached algae depends on water-depth and turbidity. Consequently, the relationship between hydraulic conditions, the

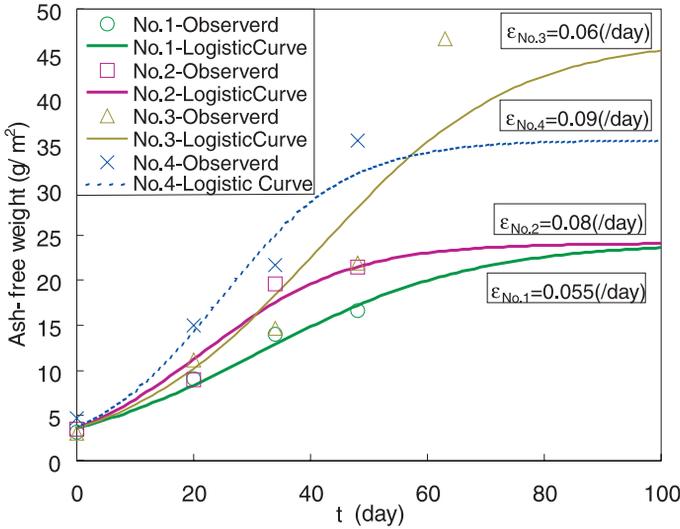


Fig. 4. – Logistic curve fitting to ash-free weight (g/m^2) of the attached algae

growth rate and environmental capacity of attached algae is discussed. Firstly, the growth rate estimation is expressed as follows:

$$\varepsilon = \varepsilon_0 (I_h / I_0) \quad (4)$$

$$\varepsilon_0 = \varepsilon_{\max} \sqrt{f_\varepsilon(U) \times g_\varepsilon(h)} \quad (5)$$

where ε_0 represents the growth rate in clear water; ε_{\max} represents the maximum growth rate of investigated data (0.1 day^{-1}); f_ε and g_ε denote the functions of velocity (U) and water-depth (h) about the growth rate, respectively; and I_h / I_0 means the remaining light rate at water-depth h , estimated by employing the following equation (Reynolds 1994).

$$I_h / I_0 = \exp(-\omega h) \quad (6)$$

in which $\omega (\text{m}^{-1})$ is the coefficient of monochromatic light extinction. This coefficient is estimated by multiplying the correction coefficient $n (\text{kg}^{-1} \text{m}^2)$

($n=20 \text{ kg}^{-1} \text{m}^2$ in the case) and turbidity $T (\text{kg}/\text{m}^3)$. The daily data of turbidity are predicted by referring to the observed data (Table 1) and water-clarity test results in the Yahagi River.

On the other hand, the environmental capacity is estimated as follows:

$$K = K_{\max} \sqrt{f_K(U) \times g_K(h)} \quad (7)$$

where K_{\max} represents the maximum environmental capacity ($46.8 \text{ g}/\text{m}^2$); f_K & g_K denote the functions of velocity (U) and water-depth (h) about the environmental capacity, respectively. That is to say, we apply the equations (Eqs. (5) & (7)) involved the meaning of the preference curves which estimated habitat suitability in the PHABSIM to evaluate magnitude of the growth rate and the environmental capacity of the attached algae in the present study.

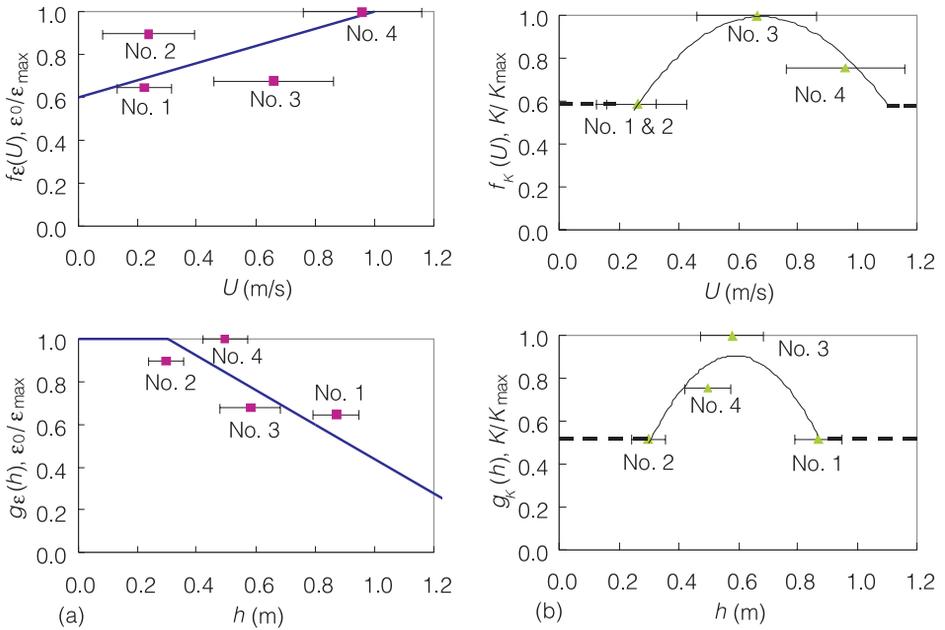


Fig. 5. – Relationship between velocity / water-depth and normalized growth rate (a) / environmental capacity (b) of the attached algae and described preference curves

Figure 5 shows the relationship between hydraulic conditions (velocity and water-depth) and the parameters about the growth of attached algae (normalized growth rate $(\epsilon_0/\epsilon_{max})$ and normalized environmental capacity (K/K_{max})) on cobbles in the each quadrate. The each plot is estimated by using the parameters (ϵ, K) of the each quadrate (No. 1 ~ 4) in Figure 4 and the relationship of Eqs. (4) – (7). The each line is described according to these data plots. The growth rate is larger in the shallow water with high velocity, and the environmental capacity is larger in the medium magnitude of velocity and depth, relatively.

Estimation of detachment rate of attached algae due to bed-load transport

Because detachment rate of attached algae depends on disturbance conditions, evaluation of the disturbance effect is needed. Therefore, the modelling that deals with the relationship between the detachment rate and bed-load transport (Kitamura *et al.* 2000) is utilized in this section. By the way, frequent floods, caused by ordinary rainfall, cannot transport the large cobbles on the substrates in the investigated channel, the cobbles serve as roughness against water

flow, and only fine bed-materials are transported. The exposed cobbles on the substrates reduce the sand tractive force among the exposed cobbles (Fujita *et al.* 2000). Hence, when the bed-load transport in cobble rivers is estimated, the following equation is set up to express the sheltering effect due to the exposed cobbles on the substrates (Tashiro *et al.* 2003).

$$\tau_{*e} = f(\delta)\tau_* = \frac{f(\delta)u_*^2}{(\sigma/\rho - 1)gd_s}, \quad f(\delta) = 1 - \delta \quad (8)$$

where $\tau_{*(e)}$ expresses the non-dimensional (effective) tractive force; δ ($= \Delta_c/d_c$, Δ_c is the exposure height of the cobble) means the non-dimensional exposure height of cobbles normalized by and the cobble diameter (d_c); f signifies the function of sheltering effects due to the roughness condition; u_* is the shear velocity; σ and ρ denote the density of the sand and water respectively; g implies the gravitational acceleration; and d_s implies the sand diameter. According to the Ashida & Michiue's Formula (Ashida & Michiue 1972), bed-load discharges q_B are estimated by adopting the τ_{*e} values.

When a particle of sand in motion collides with substratum cobble, the workload of the collision per unit area and time W_x is estimated by referring to the analysis of Ishibashi (1983) as follows:

$$W_x = \gamma q_B d_s^{1/3} u_{*e}^{2/3} \quad (9)$$

where γ represents the coefficient related to material property of cobble ($4.94 \times 10^5 \text{Nm}^{-4}\text{s}^{2/3}$); u_{*e} denote the ef-

fective shear velocity on sandy substratum. The detachment rate p can be determined by using the following equation at last.

$$p = (24 \times 3600)\alpha W_x \quad (\text{day}^{-1}) \quad (10)$$

in which α is the resistant coefficient of algae detachment ($1.23 \times 10^{-4} \text{N}^{-1}\text{m}$ for *Cladophora glomerata*, Kitamura *et al.* 2000).

SIMULATION OF GROWTH-DETACHMENT DYNAMICS OF ATTACHED ALGAE

In order to model growth-detachment dynamics of attached algae, NHSED2D, 2DH flow computation (Pornprommin *et al.* 2002) is employed for the expression of hydraulic condition. The governing equations of the depth-averaged 2D flow fields for surface flow can be written as follows:

The momentum equations

$$\frac{\partial q_x}{\partial t} + \text{div} \left(q_x \frac{\mathbf{q}}{h} - \frac{\mathbf{T}_x}{\rho} \right) = -gh \frac{\partial \zeta}{\partial x} - \left(\frac{C_f}{h^2} \right) q_x |\mathbf{q}| \quad (11)$$

$$\frac{\partial q_y}{\partial t} + \text{div} \left(q_y \frac{\mathbf{q}}{h} - \frac{\mathbf{T}_y}{\rho} \right) = -gh \frac{\partial \zeta}{\partial y} - \left(\frac{C_f}{h^2} \right) q_y |\mathbf{q}| \quad (12)$$

The continuity equation

$$\frac{\partial \zeta}{\partial t} + \text{div} \mathbf{q} = 0 \quad (13)$$

where q_x and q_y are unit discharges in each x - and y - direction; \mathbf{q} is vector of unit discharge; ζ is water surface ele-

vation; h is water-depth; \mathbf{T}_x and \mathbf{T}_y are vectors of momentum fluxes due to horizontal turbulent diffusion, g is gravitational acceleration; ρ is density of water; and C_f denotes resistance coefficient of bed-surface. When the two kinds of diameters to examine for the roughness estimation were determined, the real riverbed conditions in the channel were considered. Therefore, the large cobbles / fine sands were set at a 10 cm / 1 mm diameter. Eq. (14) is employed as the resistance law by using the equivalent sand roughness (k_s) that varies according to the exposure height of cobbles (determined by the expression $k_s = \Delta_c + d_s$).

$$\frac{U}{u_*} = \sqrt{\frac{1}{C_f}} = \frac{1}{\kappa} \ln \frac{110h}{k_s} \quad (14)$$

where U denotes the depth-averaged velocity.

The momentum fluxes due to horizontal turbulent diffusion are modeled by using eddy viscosity ν_T as follows:

$$T_{xx} = \rho \nu_T h \frac{\partial}{\partial x} \left(\frac{q_x}{h} \right) \quad (15)$$

$$T_{xy} = T_{yx} = \rho \nu_T h \left[\frac{\partial}{\partial y} \left(\frac{q_x}{h} \right) + \frac{\partial}{\partial x} \left(\frac{q_y}{h} \right) \right] \quad (16)$$

$$T_{yy} = \rho \nu_T h \frac{\partial}{\partial y} \left(\frac{q_y}{h} \right) \quad (17)$$

The eddy viscosity is modeled with shear velocity u_* and water-depth h .

$$\nu_T = \alpha u_* h \quad (18)$$

where α is empirical constant ($\alpha=0.1$).

In the present model, the boundary fitted non-orthogonal grid system is employed, and the FVM (Finite Volume Method) is employed to disperse the governing equations (Ferziger & Peirc 1997). The dispersed momentum equations are solved by the fractional step method (Ferziger & Peirc 1997) by solving Poisson equation on water-surface elevation. First the equations, which exclude the terms related to the gradient of water surface elevation, are integrated with finite time step to calculate the in-term unit discharge. Poisson equation on water-surface elevation, which is derived by substituting the in-term unit discharge into the continuity equation, is solved. The unit discharge is finally revised by calculated water-surface elevation. By repeating these processes, converged solution of flow field can be obtained.

Daily discharge and turbidity in the reach are given in Figure 6. The horizontal time scale is equal to the one in Figure 4. Because the annual maximum discharge in the reach is about 800m³/s (Tsujimoto *et al.* 2002), there is no disturbance during the investigated period. The daily turbidity is estimated by the relationship between the observed data (Table 1) and the daily discharge. According to the flow computation model (NHSED2D model, Pornprommin *et al.* 2002) and the daily discharge (Figure 6), we can compute the distribution of daily hydraulic condition in the investigated reach (Figure 2), and then can simulate the growth-detachment dynamics

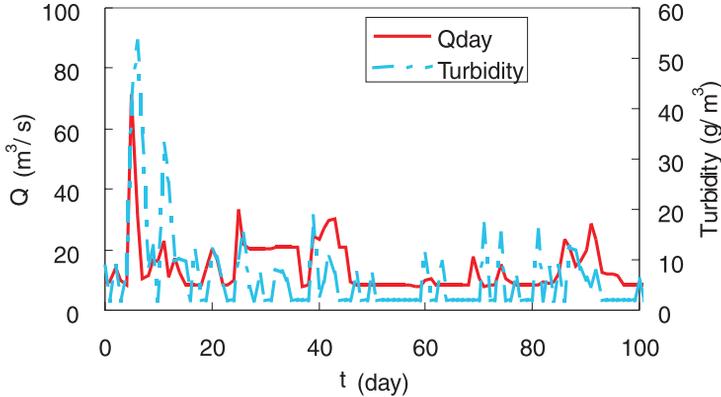


Fig. 6. – Discharge (m^3/s) and turbidity (g/m^3) in the investigated channel

of attached algae community in the each quadrat.

Initial distribution of ash-free weight of attached algae set to be uniform ($N_0=3.62\text{g}/\text{m}^2$) except at the vegetated area (Figure 2). In the simulation, the following condition is assumed: (1) if some sections were exposed to the atmosphere, a half of the ash-free weight of attached algae could be reduced on the sections per day by referring to Burns & Walker (2000); and (2) also, if some sections didn't have any ash-free weight of attached algae, 1% ratio of the initial variable ($0.0362\text{g}/\text{m}^2$) could be provided in the sections at the next time step.

Figure 7 shows the simulation result of the growth-detachment dynamics of attached algae on cobbles of each quadrat. The effect of algae detachment estimated by using Eqs. (9) & (10) can be examined by setting bed-load discharge q_B as a parameter of a calibration. Although a reproduc-

ible result is found in the simulation of quadrat No.1, the detachment effects of attached algae are overvalued in the other quadrats. By discussing the results, the problem is in phenomena of riffle or rapid section. In other words, the following effects possibly cause the disagreement: (1) biological effect due to the nest made by caddisfly larvae in the substrates; (2) disturbance efficiency of small amounts of attached algae. Firstly, about the (1) effect, high densities of caddisfly population inhabit in the substrates in the riffle or rapid section of the Yahagi River (Uchida 1997) and their high density can decrease the movability of the substrates (Statzner *et al.* 1999). And then, because the modelling of algae detachment due to bed-load transport aims at the condition of extremely blooming algae (Kitamura *et al.* 2000), the detachment of small amounts of attached algae may not be applied due to the detachment efficiency. In order to apply this kind of

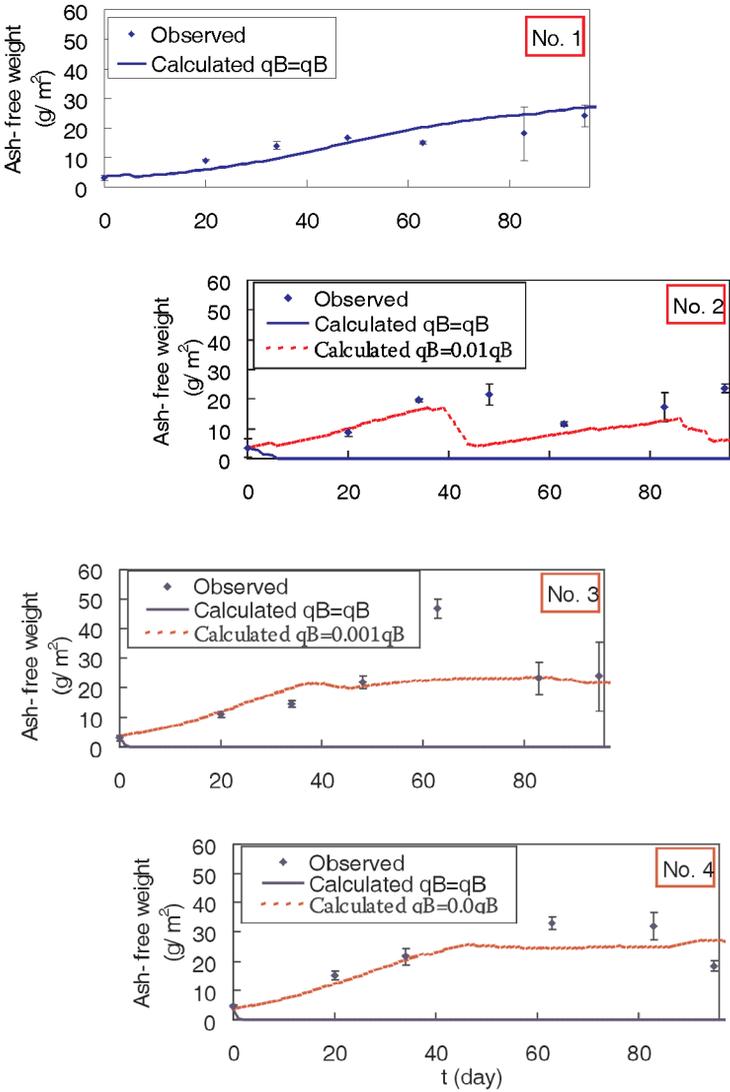


Fig. 7. – Simulation results of the growth-detachment dynamics of attached algae community on cobbles in the each quadrate by employing bed-load discharge (q_b) as a parameter of calibration

simulation to actual rivers, bed-load discharges in riffle and rapid section, i.e., sand transport on highly exposed cobble bed must be estimated suffi-

ciently by considering real phenomena as well as geomorphologic features. In other words, the algal blooming in the Yahagi River is

caused by shortage of bed-load discharge in riffle or rapid section.

CONCLUSION

In the present study, we attempted to construct new methodology for habitat evaluation by combining the two kinds of different techniques, i.e. habitat suitability evaluation and Logistic equation. We could exhibit the efficiency of the proposal methodology that understood the temporal change and the environmental characteristics of habitat condition.

Concretely, the growth-detachment dynamics of attached algae was modelled and was applied to the investigated channel in the middle reach of the Yahagi River. By investigating the habitat of attached algae in the channel, the characteristics of growth rate and environmental capacity of attached algae can be explained. On the other hand, by employing the hydraulic modelling such as algae detachment due to bed-load transport and bed-load transport on exposed cobble bed, the detachment rate related to bed-load transport was described. Finally, the simulation aimed at description of phenomena in actual river is going on developing, the proposed methodology can explain the cause of habitat degeneration due to algal blooming and reveal current problems.

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