Estimating Fresh-Water Fish Habitat Using The Phabsim System

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Abstract: This paper presents the estimation of a fresh-water fish habitat using the Phabsim System (Physical Habitat Simulation System). The Phabsim System is used as an estimation technique of fresh-water fish habitat. In the estimation of fresh-water fish habitat, HSC(Habitat Suitability Criteria) are applied. There are three HSC. In this study, the binary format which is one of the three HSC is employed. To calculate the water flow phenomenon, a 2-D shallow water equation is employed. The quasi-linear approximation of advection velocity is given by the Adams-Bashforth formula, which has second order accuracy. For the numerical approach, the FEM (finite element method) is used. For the spatial discretization, the Galerkin finite element procedure is applied. For the temporal discretization, the Crank-Nicolson method is applied. In the following, we compute the flow in the Koaze River in Saitama, Japan using the FEM. Next, using the result of FEM and data on sight, we evaluate the fresh-water fish habitat by the Phabsim System. It is clear that this analysis is useful for the estimation of fresh-water fish habitat.

Keywords: *Phabsim System; Fresh-water fish; Habitat; Finite element method*

1. INTRODUCTION

Until about forty years ago, because the quality of water in the small rivers flowing through the suburbs near big cities like Tokyo was not so bad, a lot of fish lived in rivers and kids played there.

But due to rapid urbanization, water quality has worsened, and the number of fish in the rivers has decreased. As a result, many persons who lived near the river or liked rivers have lost interest in them. As concern with the river environment has increased, people have now come to desire clean rivers where people can play with fish, and go fishing. In Japan concerns with the management of rivers, the flood control and water utilization are fundamental. But through amendment of the River Law, environmental issues have become important subjects. After this amendment to the River Law, the desire for a good river environment, including the clean flow for fish, has risen. To satisfy such desires, it is important to grasp a clear picture of the present situations of rivers. In this research, we chose the Koaze River as the objective river. Initially, to obtain the present condition of the river, field research is conducted to learn about which kinds of fish live in which parts of the river. Then, we estimate the habitat using the Phabsim system.

2. APPLY THE PHABSIM SYSTEM

The Phabsim system is a method to evaluate fresh-water fish habitats and has been used in the USA (Nakamura and Waddle, 1999). Although some researchers have had objections (Gore et al., 1988; Kuroda et al., 2001; Mathure et al., 1985), to the fundamental assumptions used in the Phabsim system which are 1) independence of depth, and velocity in channel hydraulics, and 2) suitability indexes for stream hydraulics combined through multiplication to create WUA index; it is said that this is a simple but effective method to engineering needs. Because it is easy to use, this system has come to be adopted for the evaluation of fish habitats in Japan (Ishikawa et al., 1996; Nakamura, 1994; Sutou et al., 2000). The authors chose a small river flowing through the plains near a major city and then evaluated a fresh-water fish habitat under normal discharge and steady flow conditions using the Phabsim method.

2.1. Selecting Objective Fish

In our study, the most important factor is to comprehend whether the fish can live in the objective river or not. The fresh-water fish are employed as an indicator to show the quality of the river water, the rate of aerial pollution and the progress of urbanization, respectively. In our study, to estimate the fresh-water fish habitat, *Tribolodon hakonensis* and *Zacco platypus* are adopted.

Figure 1. *Tribolodon hakonensis* (below) and *Zacco platypus* (above)

2.2. Characteristic of Fish Life

After a major rainfall in spring, *Tribolodon hakonensis* oviposit over beds covered by float stones. In some cases the oviposition is attempted after every rain. On the other hand, *Zacco platypus* oviposit from May to August. *Zacco platypus* is an omnivorous creature. For example, they prey on aquatic insects, dead animals, hard roe and young fish.

2.3. Habitat Environment

Tribolodon hakonensis is divided broadly into two categories. These are the fresh-water type and the sea run type. The fresh-water type lives upstream and downstream in the river. Also they are able to live in strongly acidic water that others cannot tolerate. On the other hand. *Zacco platypus* only lives in fresh-water river. Additionally *Tribolodon hakonensis* tends to prefer areas of slow flow in comparison with *Zacco platypus*.

2.4. Situation of Inhabitation

Tribolodon hakonensis is usually able to live in streams, driving channels, and rivers, though they cannot live in municipal rivers. *Tribolodon hakonensis* has exellent ability for moving in the flow. In fact, they can run against the rapid flow in the river. But while the number of *Zacco platypus* has increased in recent years, *Tribolodon hakonensis* has decreased in the river. To save them it is therefore important to present a suitable place for spawning.

2.5. HSC (Habitat Suitability Criteria)

To estimate fresh-water fish habitat using the Phabsim System, WUA (Weighted Usable Area) is obtained from diagrams of the HSC which have certain factors, for example water depth, velocity, bottom material (substrate), and so on. To succeed in the estimation using the Phabsim System, it is most important that values of suitability index in the HSC diagram are correct. There are several HSC in the Phabsim System.

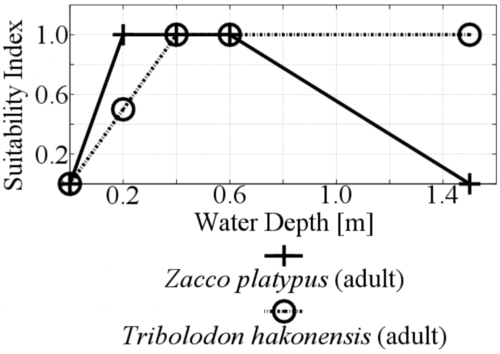

Figure 2. Estimate of HSC (Water Depth)

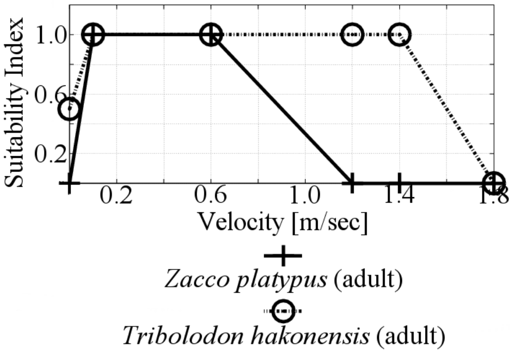

Figure 3. Estimate of HSC (Velocity)

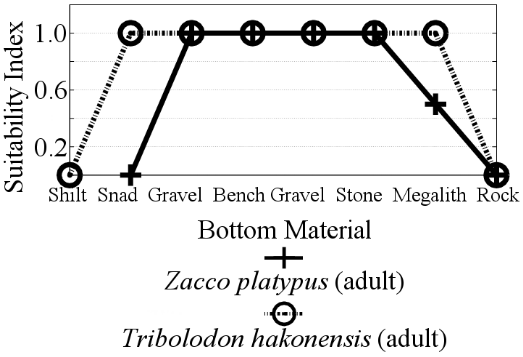

Figure 4. Estimate of HSC (Bottom Material)

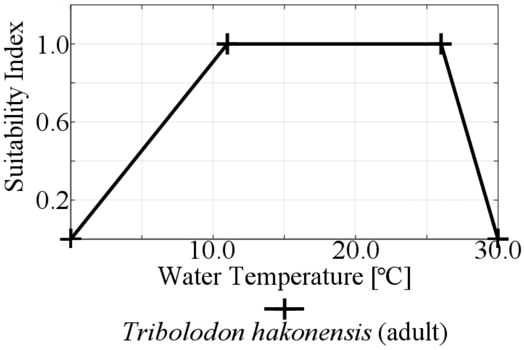

Figure 5. Estimate of HSC (Water Temperature)

In HSC, first-HSC, second-HSC, third-HSC and forth-HSC exist. First-HSC is based on the opinions of experts. In this study, the first-HSC suggested by Nakamura (Nakamura et al., 1994), is adopted. The diagram of HSC for estimating the objective fish, *Tribolodon hakonensis* and *Zacco platypus* is shown from Figure 2 to Figure 5. In these figures, the binary format is employed in the first-HSC. The binary format is the most simplified format in the estimation of suitability. In the binary format, the suitability index varies from 0.0 to 1.0 depending on the value of the horizontal axis. The value of 1.0 in suitability index from Figure2 to Figure5 indicates a high possibility for the habitat of fishes.

3. RESULT OF RESEARCH AT THE RIVER ENVIRONMENT

To recognize the reality of fresh-water fish which live in the objective river, velocity, water depth and the form of the river are researched. The Koaze River, located in the southwest part of Saitama Prefecture, is shown in Figure 6. Table 1 expresses its physical values.

Figure 6. Koaze River

Table 1. Outline of the Research Reach

Parameter	Index
Research Reach [m]	300
Normal Discharge[m^3/s]	0.5

Table 2. Outline of the Water Quality

Parameter	Index
Water Temperature[℃]	12.1
pH	8.6
DO[mg/l]	13.7
BOD[mg/l]	2.0
COD[mg/l]	5.1
SS[mg/l]	3.0

The water quality is shown in Table 2. In our study, the water quality was good enough for fish to live. The distribution of the fish was also researched in the Koaze River. To catch the fish, a net was thrown into the river at various points illustrated in Figure 7. Table 3 shows the number of fish in the stream reach. The objective fish are those more than 5.0 cm in length. Additionally it can be considered that the objective fish have the conditions needed to live in the research reach.

Table 3. The number of fish netted at each sampling point in the reach.
α: Zacco platypus, β: Tribolodon hakonensis, γ: Hemibarbs barbus, δ: Pseudorasbora parva.

Point\Species	α	β	γ	δ
A	27	1	0	0
B	10	1	0	0
C	0	4	3	0
D	4	0	0	0
E	27	0	0	0
F	8	0	0	0
G	5	0	0	0
H	5	1	0	0
I	0	0	0	0
J	0	1	2	0
K	0	0	0	0
L	13	1	0	0
M	5	0	0	1
N	1	1	0	0
O	32	4	0	0
Total	137	14	5	1

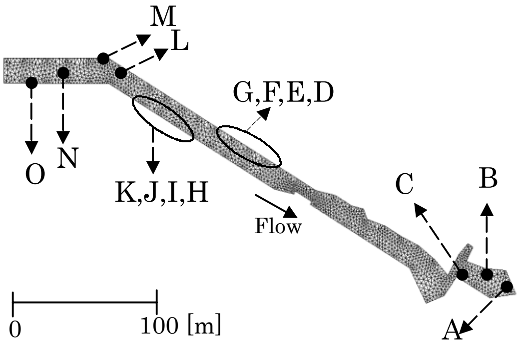

Figure 7. Sampling points in the Koaze River.

4. NUMERICAL ANALYSIS

At first, the authors considered the Phabsim System from the aspect of water quality. From Table 2 we can see that water quality in the Koaze River is suitable for these fish to live in it.

In the Phabsim System, using the terms of water temperature in Figure 5, it is expected that all of the fish can live in the reach of this river. But hydraulic variables, for example, water discharge, velocity and depth, have a great effect on the living of fish. Estimation by the next stage of the Phabsim System is carried out considering the hydraulic variables as follows.

4.1. Finite Element Method

4.1.1. State Equation

A 2-D shallow water equation is used to calculate the water flow. The 2-D shallow water equation and continuity equation can be written as follows,

$$\dot{u}_i + u_j u_{i,j} + g\eta_{,i} - \nu(u_{i,j} + u_{j,i})_{,j} + f u_i = 0 \qquad (1)$$

$$\dot{\eta} + \{(h+\eta)u_{,i}\}_{,i} = 0 \qquad (2)$$

where u_i, g, h and η are water velocity, gravity acceleration, water depth and water elevation, respectively. The coefficient of kinematic eddy viscosity ν and friction factor f are expressed as follows,

$$\nu = \frac{k_l}{6} u_* h, \qquad (3)$$

$$f = \frac{gn^2}{(h+\eta)^{4/3}} \sqrt{u_k u_k}, \qquad (4)$$

where k_l and u_* are the von Karman constant and the friction velocity, respectively. The friction velocity u_* is expressed as follows,

$$u_* = \frac{gn^2 u_k{}^2}{h^{1/3}}, \qquad (5)$$

where n is the Manning roughness coefficient. The boundary condition is expressed as follows,

$$\left.\begin{array}{lll} u_i = \hat{u}_i & on & \Gamma_d \\ \eta = \hat{\eta} & on & \Gamma_d \\ u_i = u_i n_i = \hat{u}_n & on & \Gamma_n, \end{array}\right\} \qquad (6)$$

where n_i denotes the direction cosines of the unit outward normal of the boundary, and the initial condition is expressed as follows,

$$u_i = \hat{u}_{i0} \qquad in \qquad \Omega \qquad t = t_0, \qquad (7)$$

4.1.2. Finite Element Equation

Multiplying the weighting function ω and integrating over the domain Ω for the stated equation, the weighted residual equation can be obtained as follows,

$$\int_\Omega \omega \dot{u}_i \, d\Omega + \bar{u}_i \int_\Omega \omega u_{i,j} d\Omega + g \int_\Omega \omega \eta_{,i} d\Omega - \nu\left(\int_\Omega \omega u_{i,jj} d\Omega + \int_\Omega \omega u_{j,ij} d\Omega\right) + f \int_\Omega \omega u_i d\Omega = 0, \qquad (8)$$

$$\int_\Omega \omega \dot{\eta} \, d\Omega + \bar{u}_{,i} \int_\Omega \omega h_i d\Omega + \bar{u}_i \int_\Omega \omega \eta_i d\Omega + \overline{(h+\eta)} \int_\Omega \omega u_{i,i} d\Omega = 0, \qquad (9)$$

Eq. (8) and (9) can be changed to the weighted residual equations. And by using the bubble function element (Kurahashi and Kawahara, 2001), such residual equations change to the following equations.

$$M\dot{u}_i + \bar{u}_j S_j u_i + gS_i\eta + \nu(H_{jj}u_i + H_{ji}u_j) + fMu_i = 0, \qquad (10)$$

$$M\dot{\eta} + \bar{u}_i S_i h + \bar{u}_i S_i \eta + \overline{(h+\eta)} S_i u_i = 0, \qquad (11)$$

where the coefficient matrices of the finite element equation are written as,

$$M = \int_\Omega \Phi_\alpha \Phi_\beta d\Omega, \quad S_i = \int_\Omega \Phi_\alpha \Phi_{\beta,i} d\Omega,$$

$$S_j = \int_\Omega \Phi_\alpha \Phi_{\beta,j} d\Omega, \quad H_{ii} = \int_\Omega \Phi_{\alpha,i} \Phi_{\beta,i} d\Omega,$$

$$H_{i,j} = \int_\Omega \Phi_{\alpha,j} \Phi_{\beta,i} d\Omega, \quad H_{jj} = \int_\Omega \Phi_{\alpha,j} \Phi_{\beta,j} d\Omega.$$

For the temporal discretization of the finite element equations, The Crank-Nicolson method is used.

4.2. Phabsim System

4.2.1. WUA (Weighted Usable Area)

The weighted usable area $WUA_{Q,s}$ is expressed as

$$WUA_{Q,s} = \sum_{i=1}^{n} (A_{i,Q})(CSI_{i,Q,s}), \qquad (12)$$

where $A_{i,Q}$ and $CSI_{i,Q,s}$ are the surface water area on an element, and the composite suitability index, respectively. The composite suitability index is written as

$$CSI = (SI_d)(SI_v)(SI_{ci}), \tag{13}$$

where SI_d, SI_v and SI_{ci} are the suitability index of water depth, suitability index of velocity and suitability index of bottom material, respectively.

4.3. Numerical Example

The Koaze River located in the southwest part of Saitama Prefecture is chosen as the objective site of the numerical computation. To calculate the water flow, the 2-D shallow water equation and a continuity equation are employed. The Galerkin method with bubble function element and the Crank-Nicolson method are used for spacial discretization and temporal discretization. To estimate the habitat of fish, the Phabsim System is used. Figure 2 through Figure 5 show the HSC for *Tribolodon hakonensis* and *Zacco platypus*. Figure 8 shows the cross-section at the point Y-Y.1 and Y-Y.2. The water depth and finite element mesh of the Koaze River are illustrated in Figure 9 and Figure 10. The area of a cell is about 1.2 m^2. For computation, von Karman constant k_l is 0.41 and the Manning roughness coefficient n is 0.025 and 0.015.

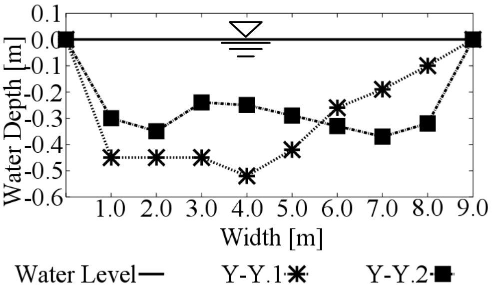

Figure 8. Cross-section of the rivers at point Y-Y.1 and Y-Y.2

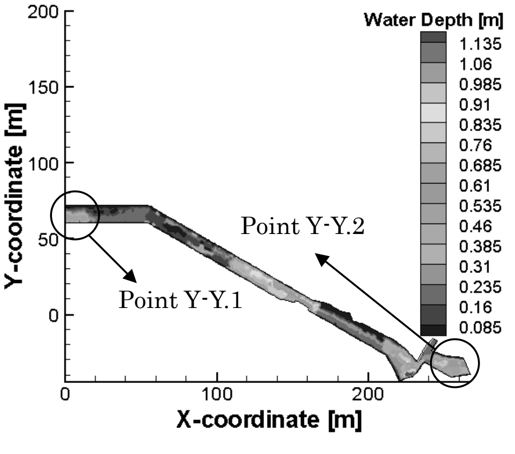

Figure 9. Water depth of the Koaze River

4.4. Results of analysis

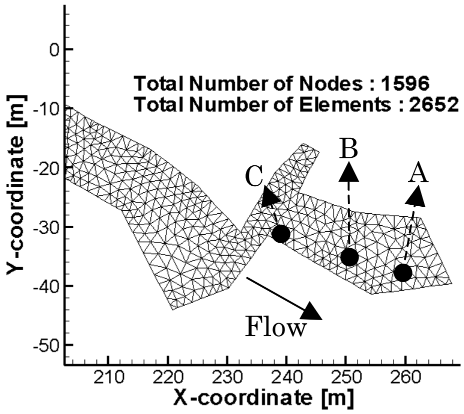

Figure 10. An example of Finite Element Mesh

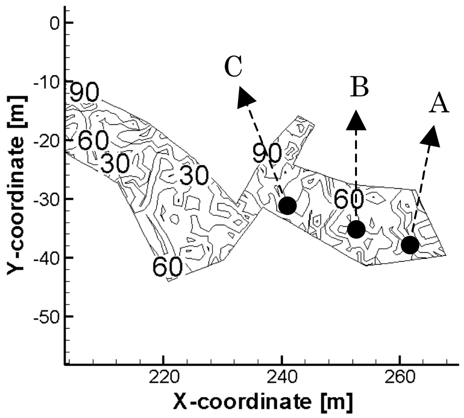

Figure 11. Estimate of WUA [%] (Q=0.5 [m^3/s]) for *Tribolodon hakonensis*(adult).

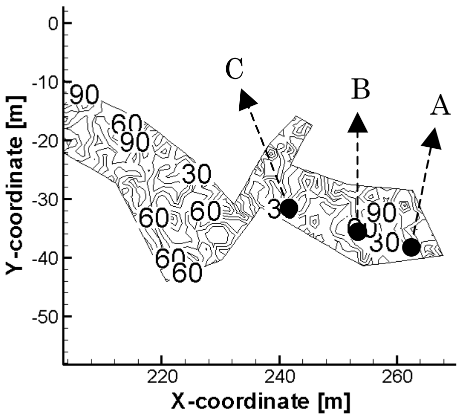

Figure 12. Estimate of WUA [%] (Q=0.5 [m^3/s]) for *Zacco platypus*(adult).

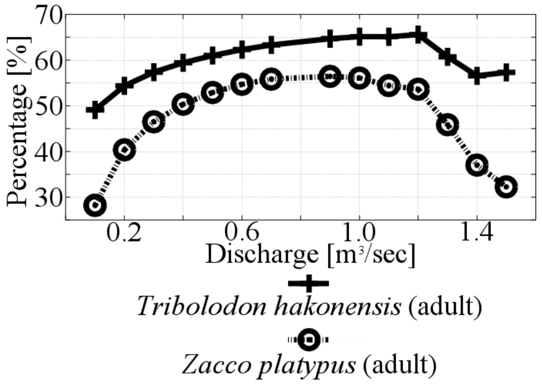

Figure 13. Estimate of WUA [%] for *Tribolodon hakonensis* and *Zacco platypus*(adult)

Results of analysis are shown in Figure 11, Figure 12 and Figure 13. Figure 11 and Figure 12 show the results of calculation near Point C in the down stream part. Numbers in the figures indicate WUA values as percentages.

Figure 11 shows that *Tribolodon hakonensis* has a high probability of living in this area. In fact, a relatively large number of *Tribolodon hakonennsis* were caught by net there. Figure 12 shows that the possibility of *Zacco platypus* living in this area is less than that of *Tribolodon hakonensis*, though many *Zacco platypus* were caught by net there. Figure 13 shows that *Zacco platypus* are fewer in quantity than *Tribolodon hakonensis*, though both of them can live there, even when discharge becomes greater than nomal.

5. CONCLUSION

1) In the evaluation of fresh-water fish habitats, it is very important to estimate hydraulic terms like the depth and velocity exactly. In the computing by the FEM, the authors divided the objective stream reach into very small cells and adopted the bubble function element for improving the accuracy of the analysis. By using such methods, we can get the good values for hydraulic terms.

2) The results of combined hydraulic quantities from computations with HSC presented by S. Nakamura (Nakamura et al., 1994), indicate the characteristics of fish habitat in the objective reach. Therefore we feel that we can use the Phabsim system for the evaluation of fish habitats in the future.

3) Though there are some differences between the results of the estimation and the results of field research, this is not unusual, and is not considered a serious problem, because numbers in Figure 11 and Figure 12 show the probability of habitat in a cell.

By investigating the coefficient in the equation for numerical analysis and HSC curve, and performing multiple field researches, we will be able to evaluate more exactly fresh-water fish habitats in rivers.

6. REFERENCES

Gore, J.A., and J.M. Nestler, Instream flow studies in perspective, *Regulated Rivers: Research and Management*, 2, 93–101, 1988.

Ishikawa, M., S. Nakamura, M. Tsukisaka, N. Azuma and Y. Nakamura, Field research to obtain the IFIM's preference curves for Japanese fresh water fishes, Bulletin of Kisarazu National Technical College, 29, 23–32, 1996 (in Japanese).

Kurahashi, T., and M. Kawahara, Decision of direction angle for bank placement based on optimal control theory, Master's thesis, Chuo University, 2001 (in Japanese).

Kuroda, N., N. Tamai, T. Chibana, Evaluation of riverine fish habitat by a rapid-pool system, *Advances in River Engineering,* 7, 303–308, 2001 (in Japanese).

Mathure, D., W.H. Bason, E.J. Purdy and C.A. Silver, A critique of the Instream Flow Incremental Methodology. *Canadian Journal of Fisheries and Aquatic Sciences*, 42, 825–831, 1985.

Nakamura, S., and T.J. Waddle, IFIM (Instream Flow Incremental Methodology), Riverfront Improvement and Restoration 1999. (in Japanese)

Nakamura, S., Summary of habitat quality index method and Instream Flow Incremental Methodology, Report of River Environment Laboratory of Toyohashi University of Technology, Department of Architecture and Civil Engineering, 9409, 1994 (in Japanese).

Sutou, T., K. Nagase, M. Michiue and O.Hinokidani, Case studies concerning quantitative evaluation of freshwater fish habitat by the Phabsim System, *Annual Journal of Hydraulic Engineering JSCE,* 44, 1203–1208, 2000 (in Japanese).