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Investigation on River Section Shape Considering Both Spawning Environment of Ayu, Plecoglossus Altivelis, and Flood Control

Investigation on river section shape considering both spawning environment of ayu, *Plecoglossus altivelis*, and flood control

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ABSTRACT

Before river improvement work, it is necessary to conduct the environmental assessment. However, the accuracy of the environmental assessment is not so high, because the preference curves of the flow depth, velocity and so on are not clear. Recently, it is pointed out that the flow depth does not affect on the suitability of spawning for ayu, *Plecoglosses altivelis*, except for very shallow flow. In contrast, the velocity strongly affects on the suitability of spawning for ayu. The preference curves of spawning suitability concerned with the flow depth, velocity and substrate were suggested. In this study, a numerical simulation using a horizontal 2-D numerical model was carried out with changing shape of cross section in Osegawa River. The suitability of spawning for ayu is predicted with those preference curves. Further, effects of changing the cross section on the flow depth when the river is flooded were compared with each case. As a result, the most suitable cross section was suggested.

Keywords: *Plecoglossus altivelis*, habitat, PHABSIM, spawning

1 INTRODUCTION

Ayu, *Plecoglossus altivelis*, is the migratory fish which inhabits in Japan, Korean peninsula and the east of the continent of China. They spawn at the lower reach of the river in autumn and drift downstream to the sea as soon as hatching. After about half year, they migrate to the upper and middle reach of the river in school and feed planktons firstly. After that they feed on attached algae on rocks. Sometimes some ayu makes territory which covers about 1m^2. Such ayu attacks to the other ayu which enter the territory. The body lengths of migrating ayu in spring are about 6-8cm. Ayu grows up rapidly in the river. The body lengths of some ayu reach to 30cm. In autumn, mature ayu spawns at the lower reach of the river and then dies (Ishida, 1959).

The ayu is one of the most important fish for fishery from a point of view of economy in Japan. Further the environmental assessment law was established in 1997. Therefore, it is necessary to conduct the environmental assessment before construction of the hydraulic structures in rivers. On the other hand, the ayu can inhabit both in pools and rapids. In contrast, ayu can spawn only in the rapids. Therefore, to preserve the rapid is quite important in particularly.

Before river improvement work, it is necessary to conduct the environmental assessment. However, the accuracy of the environmental assessment is not so high, because the preference curves of the flow depth, velocity and so on are not clear. Recently, it is pointed out that the flow depth does not affect on the suitability of spawning for ayu, *Plecoglosses altivelis*, except for very shallow flow. In contrast, the velocity strongly affects on the suitability of spawning for ayu. The preference curves of spawning suitability concerned with the flow depth, velocity and substrate were suggested.

In this study, a numerical simulation using a horizontal 2-D numerical model was carried out with changing shape of cross section in Osegawa River. The suitability of spawning for ayu is predicted with those preference curves. Further, effects of changing the cross section on the flow depth when the river is flooded were compared with each case. As a result, the most suitable cross section was suggested. Such a proposal is firstly proposed in Japan.

2 TARGET RIVER

Figure 1 shows the map of Nobeoka city where is located at the middle and eastern part of Kyushu Island, Japan. The Gokasegawa River, Hourigawa River and Kitagawa River are running through the Nobeoka city. Those rivers belong to Class A river. The administrator of the Class A river is Ministry of Land, Infrastructure and Transport (MLIT). The Gokasegawa River has a branch, i.e., Osegawa River. Those rivers reach to the Pacific Ocean. The length and watershed catchment area of the Gokasegawa River are 106Km and 1820Km^2, respectively.

The Gokasegawa River has three spawning beds of the ayu, i.e., Hyakken, Misu and Agata Rapid (see Nagaya et al., 2004). Those rapids were also described as the black circle in Figure 1. Those rapids were located at the downstream, however, do not generally receive the tidal effect from the sea. The Agata Rapid is located between 3k800m and 4k200m from the river mouth.

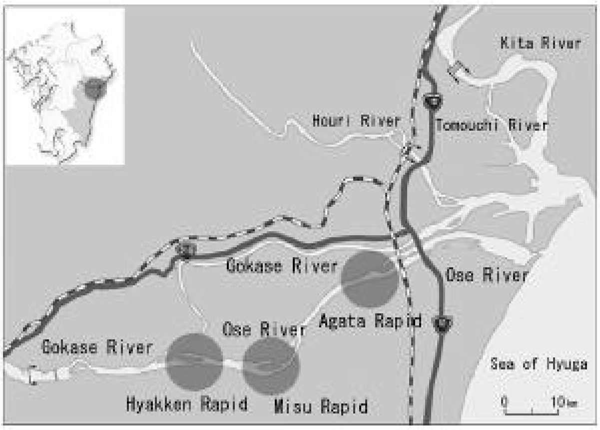

Fig.1 Three spawn beds in Gokasegawa River

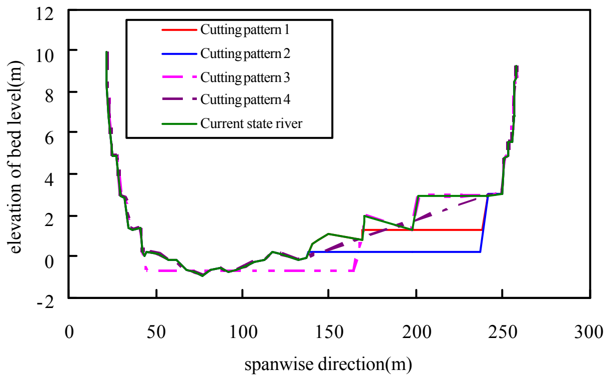

Fig.2 Cross section of cutting pattern at 3k800m

3 INVESTIGATION ON RIVER SECTION SHAPE CONSIDERING BOTH SPAWNING ENVIRONMENT OF AYU, AND FLOOD CONTROL

A lot of floods have been occurred in this river, so that some damages have been given. On this account, a large-scale river improvement in Osegawa is planned. The shape of the cross section of the Osegawa River is compound. Therefore, it is quite easy to decrease the flood damage, because much discharge may flows if the flood plain is eliminated. In contrast, the spawning season of ayu in Kyushu Island, Japan is from September to December. They spawn over the river beds in the rapids at the lower reach. If the rapids are destroyed by the river improvement, the ayu can not spawn. Therefore, it is necessary to conduct the environmental assessment, i.e., spawning of ayu is possible or not, before construction of the hydraulic structures in rivers. Unfortunately, it is not possible to predict the water level when the river is flooded and also the suitability of spawning, before calculating such values. Therefore, some samples of cross sections are proposed on the basis of past rive improvement and calculations must be conducted. And finally, the most suitable cross section will be pocked up from the point of view of spawning suitability and flood control.

A few cutting pattern, i.e., cutting pattern 1, 2, 3 and 4 around the Agata Rapid, are proposed in this study. The cutting region is located from 3k400m to 4k800m. Figure 2 shows the sample of 4 cross sections and current state section and Figure 3 shows the plane view near the cutting area. The cutting area is drawn by red. The cutting area in the horizontal plane in both cases (cutting pattern 1, 2 and 3) is almost the same. Such area is located at the inner bank in the meandering channel. The bed elevation in the cutting area is only different from each other (see Figure 2).

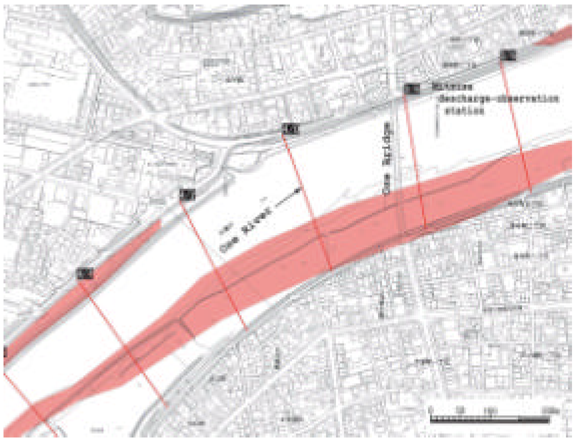

Fig.3 Plane view of cutting area (3k600-4k400)

4 2-D MODEL AND PHABSIM

4.1 2-D MODEL

A horizontal 2-D numerical model in Cartesian coordinates system was described as following equations:

$$\frac{\partial h}{\partial t}+\frac{\partial M}{\partial x}+\frac{\partial N}{\partial z}=0 \tag{1}$$

$$\frac{\partial M}{\partial t}+\frac{\partial U_m M}{\partial x}+\frac{\partial W_m M}{\partial z}+gh\frac{\partial H}{\partial x}=-\frac{\tau_{0x}}{\rho}-h\frac{\partial \overline{U_m'U_m'}}{\partial x}-h\frac{\partial \overline{U_m'W_m'}}{\partial z} \tag{2}$$

$$\frac{\partial N}{\partial t}+\frac{\partial U_m N}{\partial x}+\frac{\partial W_m N}{\partial z}+gh\frac{\partial H}{\partial z}=-\frac{\tau_{0z}}{\rho}-h\frac{\partial \overline{U_m'W_m'}}{\partial x}-h\frac{\partial \overline{W_m'W_m'}}{\partial z} \tag{3}$$

In which x and z are the streamwise and spanwise coordinate, respectively. t is the time, g is the gravitational acceleration, ρ is the density of water, h is the flow depth, H is the water level, τ_0 is the bed shear stress. U_m and W_m are the depth averaged velocity in the x and z direction, respectively. $\overline{U_m'U_m'}$ and $\overline{U_m'W_m'}$ and $\overline{W_m'W_m'}$ are the depth averaged Reynolds stress in the x and z directions, respectively. M and N are the discharge flux in the x and z directions, respectively. The depth averaged Reynolds stresses are modelled as follows.

$$-\overline{U_m'U_m'}=2D_h\left(\frac{\partial U_m}{\partial x}\right)-\frac{2}{3}k \tag{4.a}$$

$$-\overline{U_m'W_m'}=D_h\left(\frac{\partial U_m}{\partial y}+\frac{\partial W_m}{\partial x}\right) \tag{4.b}$$

$$-\overline{W_m'W_m'}=2D_h\left(\frac{\partial W_m}{\partial y}\right)-\frac{2}{3}k \tag{4.c}$$

$$D_h=0.3hu_* \tag{5}$$

In which D_h is coefficient of eddy viscosity, k is the depth averaged turbulence energy, u_* is the friction velocity. The generalized coordinate system proposed by Nagata et al.(2000) was used in order to apply to the complicated landform of the actual river. Therefore, Eqs.(1)-(3) were changed to the generalized coordinate system (see Nagaya & Matsuo, 2002).

4.2 CALCULATION CONDITIONS

It is better to use small mesh and also large area when the calculation was conducted. Unfortunately, computer power and calculation cost are limited, so that the mesh sizes of the streamwise and spanwise directions were set to be 100m and 10m, respectively.

Table 1 shows the calculation condition. Three sets of discharges were given. 33.5m^3/s (185-day discharge) corresponds to normal condition, 50m^3/s (185-and 75-day discharge) corresponds to spawn condition, because it is well known that ayu spawns during and after the small flood and 1,930m^3/s (annual mean maximum discharge) corresponds to large flood. Each discharge are given at the inlet edge of calculation domain The flow depth at Mitsuse water level observation station, where is located in the calculation region as shown in Figure 3, is given from stage discharge curve (H-Q curve). The time interval Δt was set to be 0.1s. It is well known that the Manning's coefficient of roughness n depends on the bed surface material. Therefore, Manning's coefficient of roughness n was set in the rage between 0.020 to 0.080s/m$^{1/3}$ on the basis of the bed surface material. The judge of convergence of calculation was conducted whether the flow becomes steady or not.

Table 1 calculation condition

upstream	inlet discharge was given as following discharge phase A. 33.5m^3/s: corresponding to185-day discharge phase B. 50m^3/s: corresponding to discharge between 185-and 75-day discharge phase C. 1,930m^3/s : corresponding to annual mean maximum discharge
downstream	predicted flow depth at Mitsuse water level observation station, where is located in the calculation region, was given. Predicted flow depth is calculated from H-Q curve
Manning's coefficient of roughness	high water channel: 0.020~0.080s/m$^{1/3}$ low water channel: 0.030~0.033s/m$^{1/3}$
time interval	0.1s
judge of convergence of calculation	when flow becomes steady

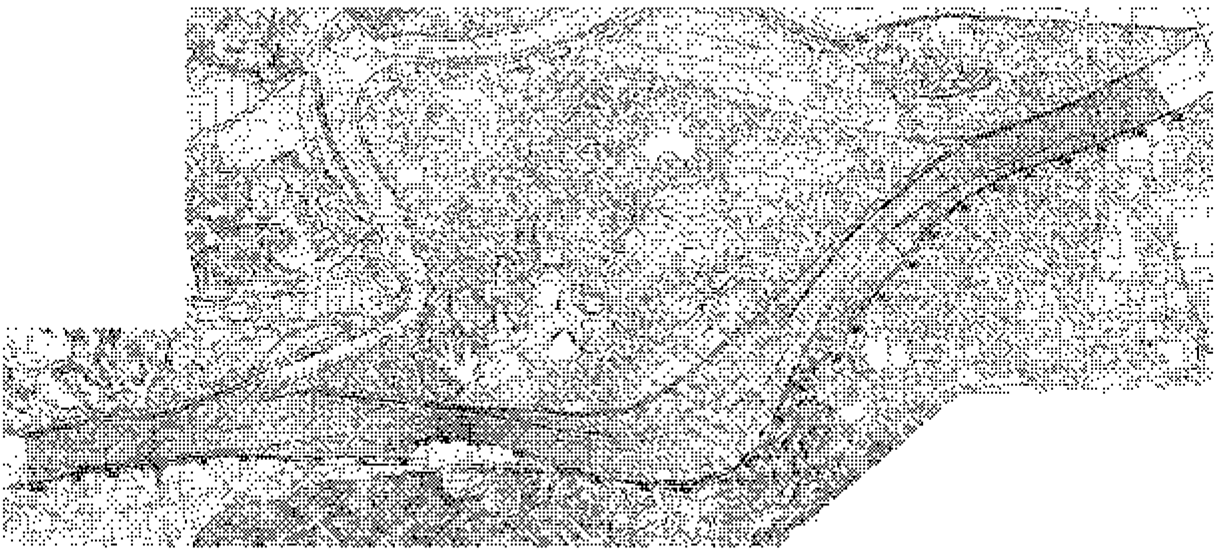

Fig.4 Calculation domain includes three spawning bed of ayu.

4.3 PHABSIM

One of the most famous environmental assessment methods is PHABSIM. The available physical habitat is evaluated from the composite suitability index CSI . CSI is calculated from the suitability index such as flow depth $SI(h)$, velocity $SI(v)$, substrate $SI(s)$, cover $SI(c)$ and so on.

$$CSI = SI(h)\times SI(v)\times SI(s)\times SI(c)\times\cdot \tag{6}$$

The parameters on the right hand side in Eq.(6) are chosen according to the fish species. The suitability of spawning for ayu can be also evaluated from Eq.(6). The cover may not affect on the suitability of spawning for ayu, due to the area of the spawning bed of ayu is located downstream of the river. Therefore, the composite suitability index CSI of spawning for ayu is calculated by the following equation.

$$CSI = SI(h)\times SI(v)\times SI(s) \tag{7}$$

Nagaya et al.(2004) and Onitsuka et al.(2005) pointed out that the effects of the flow depth $SI(h)$ on the suitability of spawning for ayu are quite small in compared with that of the velocity except for very shallow flow. When the flow depth is lower than the fish height, they cannot swim. Therefore, the preference curve of the flow depth $SI(h)$ is described as follows:

$$\begin{aligned} SI(h) &= 33.3h \ \ (0 \le h(\mathrm{m}) < 0.03) \\ SI(h) &= 1 \ \ (0.03 \le h(\mathrm{m})) \end{aligned} \tag{8}$$

Unfortunately, the effect of the substrate $SI(s)$ is not cleared at present. In contrast, the velocity strongly affects on the suitability of spawning for ayu. The preference curve of the velocity for spawning of ayu $SI(v)$ is suggested by Onitsuka et al.(2005) as shown by the following equation.

$$\begin{aligned} SI(v) &= 0 \ \ (0 \le U_m(\mathrm{m/s}) < 0.3) \\ SI(v) &= 3.3U_m - 1 \ \ (0.3 \le U_m(\mathrm{m/s}) < 0.6) \\ SI(v) &= 1 \ \ (0.6 \le U_m(\mathrm{m/s}) < 1.0) \\ SI(v) &= -1.4U_m + 2.4 \ \ (1.0 \le U_m(\mathrm{m/s}) < 1.7) \\ SI(v) &= 0 \ \ (1.7 \le U_m(\mathrm{m/s})) \end{aligned} \tag{9}$$

Although the effect of the substrate was not cleared, the suitability of spawning for ayu may be predicted from Eqs.(7)-(9) under the assumption that $SI(s)$ is always 1.0.

5 RESULTS AND DISCUSSIONS

5.1 Velocity

Fig.5 shows the velocity contour in the phase A (185-day discharge). The numerical indicators at the left bank side in the figures show the distance from the river mouth. The velocity at the left bank in the improved region (3K400 to 4K800) increases in the current state, because the centrifugal force is generated due to the longitudinal shape of river is curved here. In the case 1(cutting pattern 1), water flows over the flood plain at the right bank side. The velocity over the flood plain is comparably low. In the case 2(cutting pattern 2), the velocity in the improved area decreases in compared with that of the current river channel, because the cross sectional area is increased. In the case 3(cutting pattern 3), the velocity of outer bank increases remarkably in compared with that of the current river channel. This is because the centrifugal force is generated there. In the case 4(cutting pattern 4), the velocity field is similar to the current river channel.

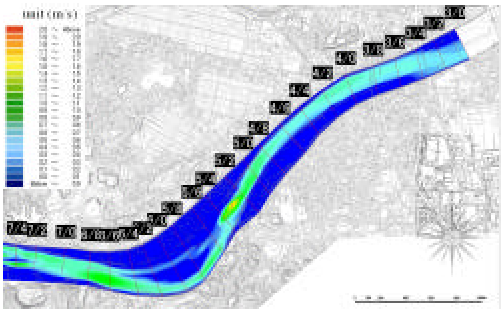

Fig.5(a) Velocity contour when current river channel
(phase A: 33.5m^3/s)

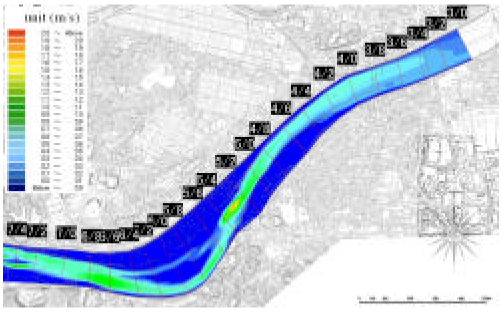

Fig.5(b) Velocity contour in case 1
(phase A: 33.5m^3/s)

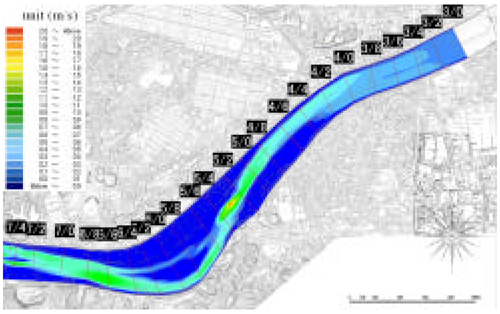

Fig.5(c) Velocity contour in case 2
(phase A: 33.5m^3/s)

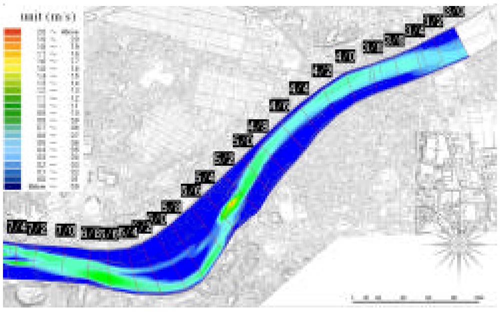

Fig.5(d) Velocity contour in case 3
(phase A: 33.5m^3/s)

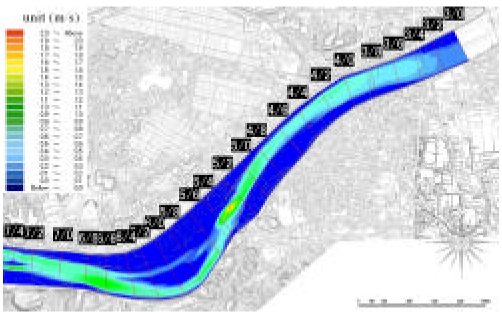

Fig.5(e) Velocity contour in case 4
(phase A: 33.5m^3/s)

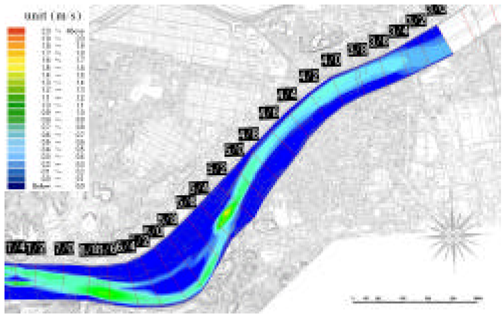

Fig.6(a) Velocity contour when current river channel
(phase B: 50m^3/s)

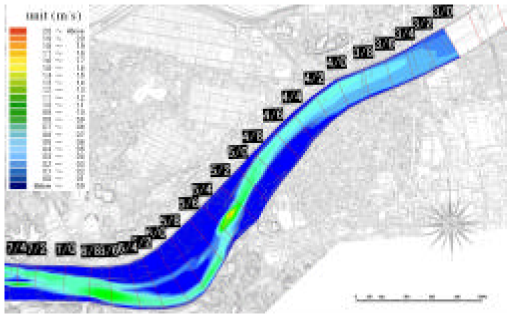

Fig. 6(b) Velocity contour in case 1
(phase B: 50m^3/s)

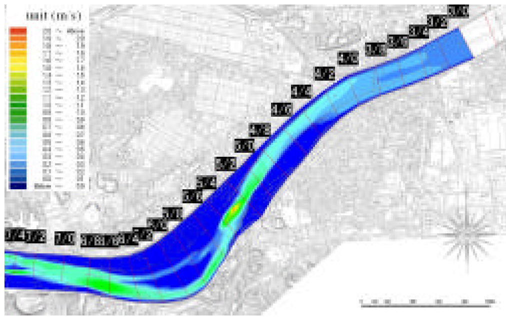

Fig. 6(c) Velocity contour in case 2
(phase B: 50m^3/s)

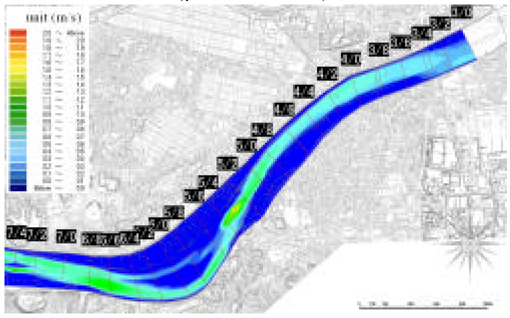

Fig. 6(d) Velocity contour in case 3
(phase B: 50m^3/s)

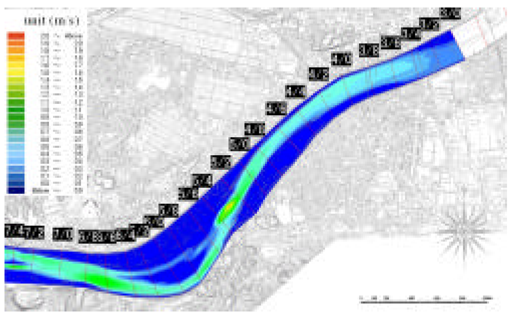

Fig. 6(e) Velocity contour in case 4
(phase B: 50m^3/s)

Fig.6 shows the velocity contour in the phase B (185-and 75-day discharge). The flow fields in each case are quite similar to those in phase A. Therefore, considerations are omitted.

Fig.7 shows the velocity contour in the phase C (annual mean maximum discharge). A large difference between each case is not observed. This may because the inertial force is quite large when the flood, so that the effects of the cross section shape on the flow fields becomes small.

In the phases A and B, high velocity area is seen near the sand bank which is located at the upstream area of the calculation domain. This area is corresponding to the Hyakken Rapid. High velocity is also seen at the upstream region of the corner where is located at the center of this figure. This area is corresponding to the Misu Rapid. These imply that the accuracy of this calculation is high. On the other hand, in the phase C, the discharge is large so that the velocity becomes high. Velocity is in the range between 2.0m/s and 3.0m/s in especially the Hyakken rapids and Misu rapids. Moreover, velocity is also high at the right bank near the Agata rapids.

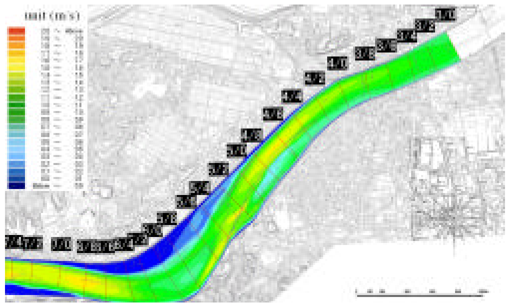

Fig.7(a) Velocity contour when current river channel (phase C: 1,930m^3/s)

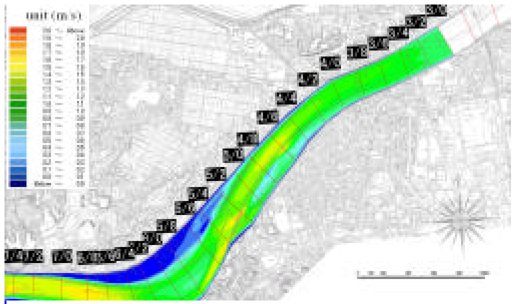

Fig.7(b) Velocity contour in case 1 (phase C: 1,930m^3/s)

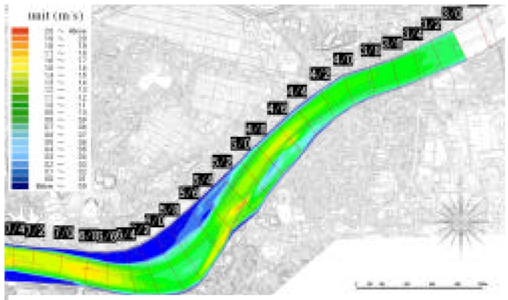

Fig.7(c) Velocity contour in case 2 (phase C: 1,930m^3/s)

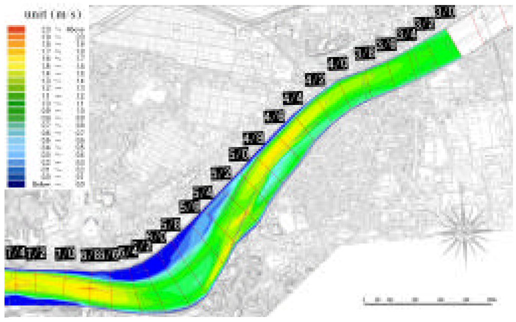

Fig.7(d) Velocity contour in case 3 (phase C: 1,930m^3/s)

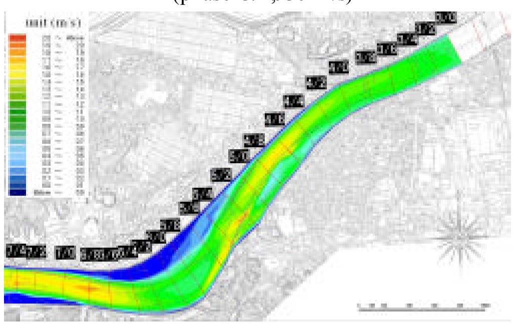

Fig.7(e) Velocity contour in case 4 (phase C: 1,930m^3/s)

5.2 Evaluation of CSI

Nagaya et al.(2005) calculated the current flow fields near the Agata rapid. It was found that the accuracy of the calculation is quite high, with comparison measured flow depth and calculated one. They predict the CSI (composite suitability index) of spawning of ayu on the basis of the numerical result. As a result, the haul of ayu can be predicted with high accuracy. The numerical model and environmental assessment method (PHABSIM) is the same as Nagaya et al.(2005)'s. Therefore, it can be said that the evaluation of the flow field and CSI in the current situation is reliable.

Fig.8 shows the contour of CSI concerned with the ayu spawning which is calculated by using Eqs.(7)-(9) for each case. CSI is considered only in the phase B (50m^3/s discharge), because a lot of ayu spawn after the small flood. In the case 1, CSI at the left bank side increases. Moreover, the spawning propriety area is generated on the flood plain at the right bank side. In the case 2, CSI decreases overall, so that the spawning propriety area reduces, because the velocity becomes small more than 0.3m/s as the cross sectional area increases, so that suitability index of velocity becomes zero (see Eq.(9)). In the case 3, CSI increases, because the velocity increases due to the shape of the river bed is flat. In the case 4, the characteristics of CSI is similar to that in the case 3.

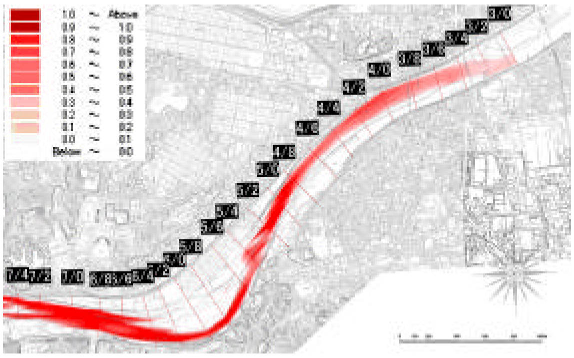

Fig.8(a) CSI contour when current river channel
(phase B: 50m^3/s)

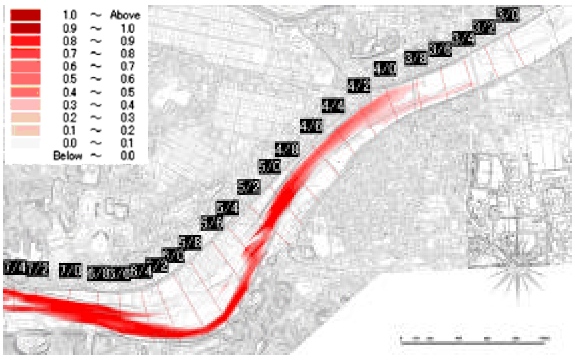

Fig.8(c) CSI contour in case 2
(phase B: 50m^3/s)

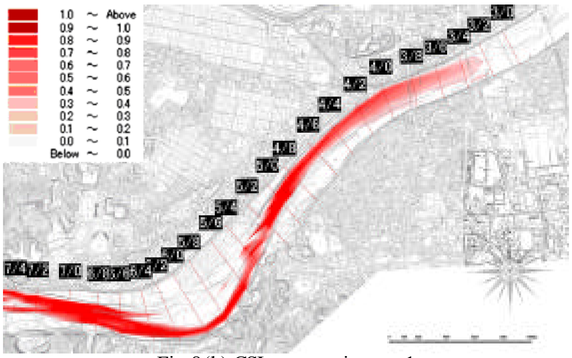

Fig.8(b) CSI contour in case 1
(phase B: 50m^3/s)

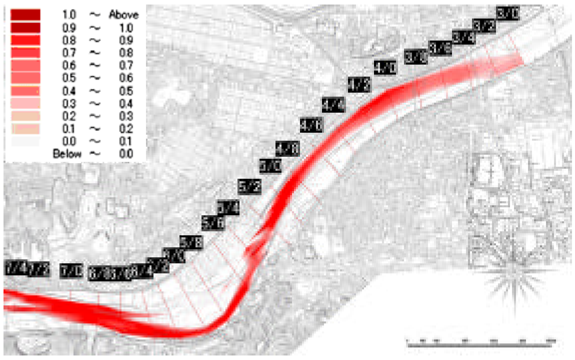

Fig.8(d) CSI contour in case 3
(phase B: 50m^3/s)

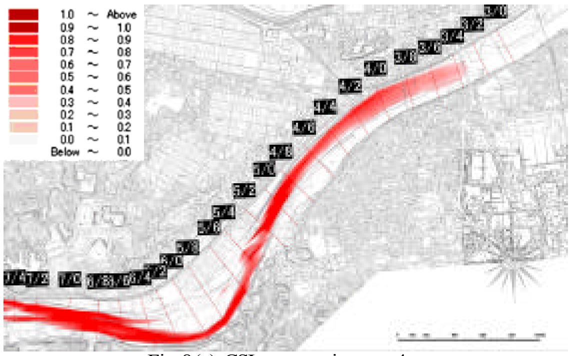

Fig.8(e) CSI contour in case 4
(phase B: 50m^3/s)

5.3 A proposal of cutting pattern considering both of flood control and spawning suitability for ayu

5.3.1 Effect of river improvement on water level decrease

It is necessary to confirm the effect of the river improvement on the water level. Fig.9 shows the water level in the streamwise direction for each case.

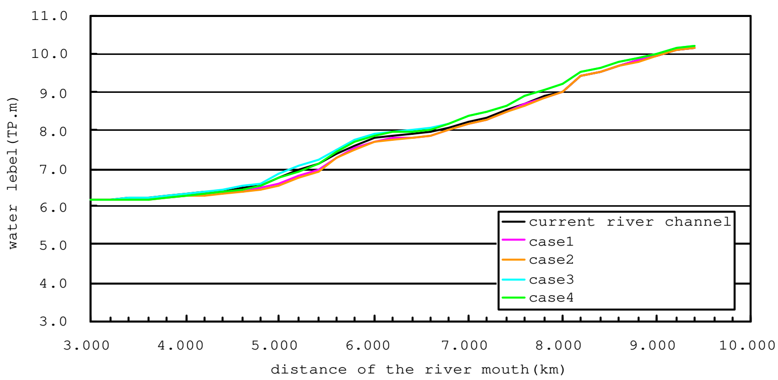

Fig.9 Comparison of water level belong streamwise direction for each cases when discharge is 1,930m^3/s

In the cases of 3 and 4, the water levels rise than that of the current river channel, so that flood risk rises. On the other hand, in the cases of 1 and 2, the water levels decrease in compared with that of the current river channel. For example, decrease levels at 5K000 in cases 1 and 2 are 0.14m and 0.20m, respectively.

5.3.2 Weighted Usable Area(WUA) of spawning environment of ayu

To understand CSI (composite suitability index) of spawning for ayu quantitatively, weighted usable area (WUA) is calculated from the following expressions.

$$WUA = \int_A (CSI) dA \qquad (10)$$

Fig.10 shows the *WUA* for each case in the phase B (185-and 75-day discharge). WUA in cases 1, 3 and 4 increases and that in case 2 decreases in compared with that of current river channel. It can be said that case 3 is the most suitable case only from the point of view of spawning suitability.

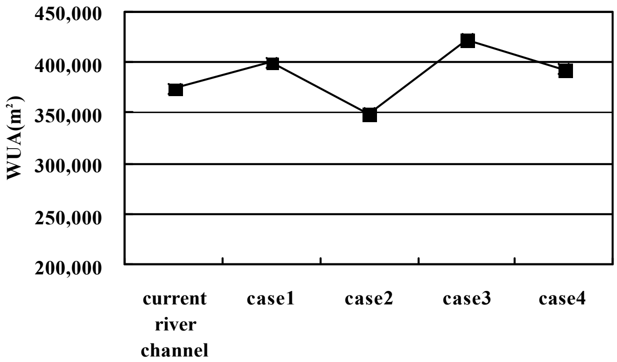

Fig.10 *WUA* in each case (phase B: 50m^3/s)

5.3.3 A proposal of cutting pattern considering both of flood control and spawning suitability for ayu

The effect of river improvement on water level decrease and spawning suitability for ayu are calculated by the following equation and shown in Table 2.

Table.2 Comprehensive evaluation

	Case 1	Case 2	Case 3	Case 4
Effect on water level	1.02	1.03	0.98	0.99
Effect on spawning suitability for ayu	1.07	0.93	1.13	1.05
average	1.04	0.98	1.05	1.02

$$\text{Effect on water level} = \frac{\text{water level at 5k000 in current river state}}{\text{water level at 5k000 in phaseB}} \qquad (11.a)$$

$$\text{Effect on spawning suitability for ayu} = \frac{\text{WUA in pahseB}}{\text{WUA in current river state}} \qquad (11.b)$$

The water levels in the cases 3 and 4 increase, due to the "Effect of water level" decrease, so that those cases are not to be adopted to the river improvement, although the spawning area increases in compared with that of current river state ("Effect on spawning suitability for ayu" increases in both cases). In contrast, the water levels in the cases 1 and 2 decrease. However the spawning area decreases in the case 2. Therefore, it was judged that case-1(flood channel cutting down) is most suitable cross section.

6 CONCLUSIONS

The Osegawa river is located in Kyushu Island, Japan. Some floods have been occurred in this river. The shape of the cross section of the Osegawa river is compound.

Therefore, it is quite easy to decrease the flood damage, because much discharge may flows if the flood plain is eliminated. In contrast, it is necessary to consider whether the ayu can inhabit or not when a river improvement plan is formed from a point of view of inland fishery. In this study, a river improvement method, in which the ayu can spawn, was proposed by making use of a 2-D numerical method and also PHABSIM. This kind of proposal is firstly proposed in Japan.

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