IMPACT OF SHISHAMO SPAWNING SITES OF AZUMA RIVER, HOKKAIDO IN VARIOUS FLOW AND HIGH CONCENTRATION SILT CONDITIONS

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On September 6, 2018, a magnitude 6.7 earthquake occurred in the eastern part of the Hokkaido Iburi Region, causing more than 6,000 surface landslides in the Azuma River basin. There are concerns about the impact of fine sediment runoff from the landslides and sedimentation on riverbeds of shishamo spawning sites. With these backgrounds, we investigated the suitable physical parameters for shishamo spawning based on long-term monitoring data conducted by Hokkaido Government. Subsequently, using a two-dimensional flow and bed deformation model, the impact of various discharge scales and high concentration silt on shishamo spawning sites were identified. The results showed that common spawning sites for shishamo are located at depths of 0.3 to 0.7 m and bottom velocities of 0.2 to 0.5 m/s, where the occupancy ratio of coarse grain sediment is high. While bottom velocities faster than 0.6 m/s and high silt sedimentation are not suitable as a spawning ground. Numerical simulation explained that the optimum locations of spawning become widespread when the flow rate is higher than the average discharge in winter month (spawning season) of 5.0 m^3/s. Most fine-grain sediment is transported to the river mouth without sedimentation in the low flow channel, suggesting that the effects of fine-gradient sediment on spawning may be small so far. It should be noted, however, that sedimentation tends to occur on the inner banks of meanders, in large areas of the river width, and along the riverbanks. The Azuma River has low discharge during the winter months, so it is necessary to maintain as much flow as possible.

Keywords: s*hishamo smelt spawning, Azuma River, earthquake, high silt concentration, numerical simulation*

1 INTRODUCTION

The shishamo smelt (*Spirinchus lanceolatus*) is a useful fishery resource in Hokkaido and is found only in the western part of the Pacific Ocean. They grow in the sea and spawn in rivers. As famous spawning rivers in Hokkaido, the Mukawa River, Tokachi River, Shin-Kushiro River, and Azuma River are well known [1]. However, on September 6, 2018, a magnitude 6.7 earthquake occurred in the eastern part of the Hokkaido Iburi Region, causing more than 6,000 surface failures in the Azuma River basin (Figure1). The area of surface landslides in the upper reaches of the Azuma River accounts for approximately 11.1% (29.0 km^2) of the river basin [2]. Therefore, by the fishing industry in the Azuma River, there is a concern about the impact on the shishamo spawning sites due to fine sediment runoff induced by rainfall and its deposition in the river channel.

The general ecology of the shishamo has been reported in several previous reports [1][4]. Filed survey results showed that adults migrate upstream from the coast to rivers to spawn from October to December, and their eggs hatch from April to May of the following year. Spawning sites are preferred at depths of 0.02 to 4.0 m, with a grain size of 0.425 to 2.0 mm (coarse sand) in the riverbed and a bottom velocity of 0.3 to 0.6 m/sec [1][4]. Laboratory experiments based on the field survey results confirmed a stronger preference for areas with bottom velocities of less than 0.6 m/sec than for bed material, based on the swimming ability of adult fish and the concern of detachment of spawning eggs [1][4]. Furthermore, the effect of silt-clay deposition on spawning sites was confirmed by a decrease in survival rate at deposition thicknesses of 4 mm or greater [4]. In recent years, shishamo abundance has declined significantly, but knowledge of the effects of changes in the physical environment on spawning is limited.

In this study, we analyzed the field survey data conducted by the Hokkaido Government over the past 11 years to understand the suitable spawning sites for shishamo in the lower reaches of the Azuma River. Then, the characteristics of fine-grained sediment deposition in the lower reach of the Azuma River were estimated by the two-dimensional flow and morphodynamics model.

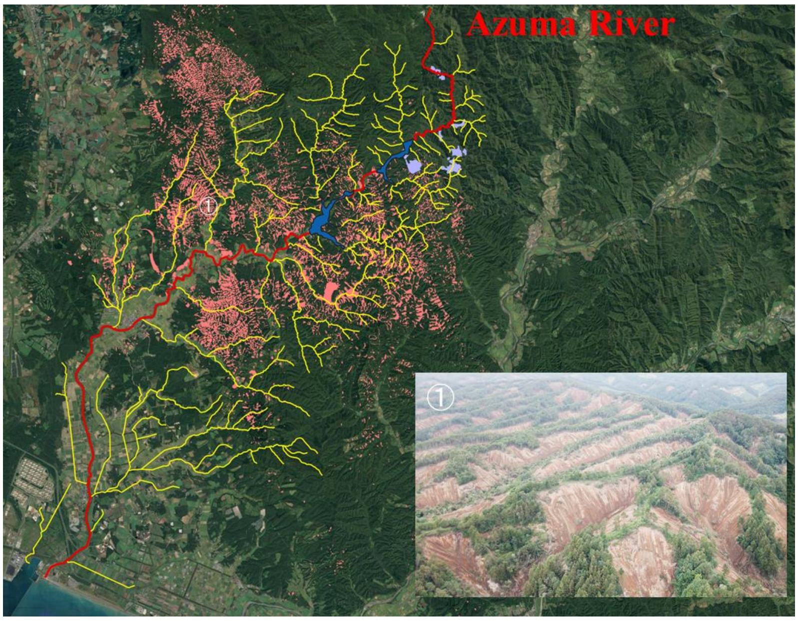

Figure 1. Landslide areas in the Azuma River Basin following the 2018 Hokkaido Eastern Iburi earthquake, (Pink-colored places indicate landslide areas published in geojson format at the URL of https://www.gsi.go.jp/BOUSAI/H30-hokkaidoiburi-east-earthquake-index.html)

2 FIELD SURVEY DATA IN AZUNA RIVER

2.1 AZUMA RIVER

Azuma River has a relatively gentle gradient of 1/670 to 1/1640, with a basin area of 382.9 km^2 and a channel length of 52.3 km. Azuma city is located upstream of the Azuma Bridge, 17.6 km from the mouth of the river. There is one gauging station on the river at the Azuma Bridge as shown in Figure 2,.

2.2 SHISHAMO SURVEY DATA AND DATA ANALYSIS

The main shishamo spawning sites are from the river mouth to about 13 km upstream, where there is an intake weir with no fishway. Figure 2 shows the locations of the field survey by the Hokkaido Government. Surveys were conducted every 1 km within an area ranging from 2km to 12 km from the river mouth of the river. At each site, survey points were set up near the left, center, and right banks for quantitative sampling of eggs and channel bed material using quadrat-frame (25 × 25 cm) server nets. In addition, at the quantitative sampling points, the flow velocity near the riverbed was measured. Spawning ground surveys have been conducted since 1994, but this study will cover a total of 11 years from 2010 to 2020 when discharge data are available. To understand long-term changes in the physical environment of the lower area in the Azuma River and the number of shishamo eggs found on spawning beds, we compiled data on daily flow, longitudinal distribution of riverbed material, and the number of shishamo adults and spawned eggs from 2010 to 2020.

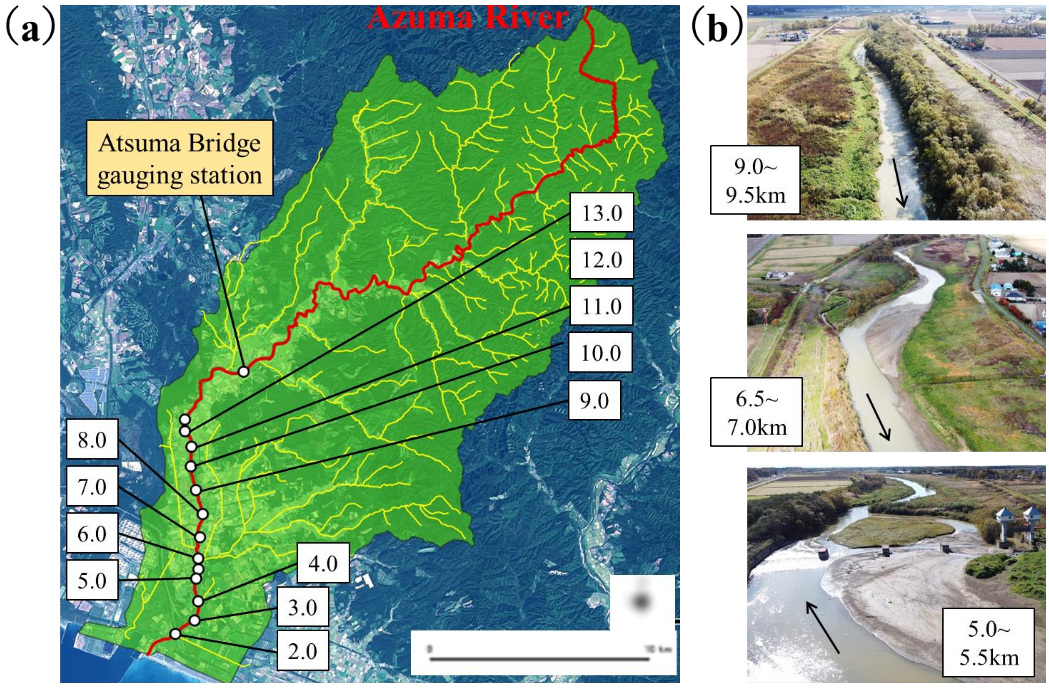

Figure 2. Survey area in the lower reach of the Azuma River conducted by the Hokkaido Government, (a) The numbers in the figure represent the survey cross-sections' location and the distance from the river mouth, (b) Photographs taken by UAV（2020/10/16～10/26）

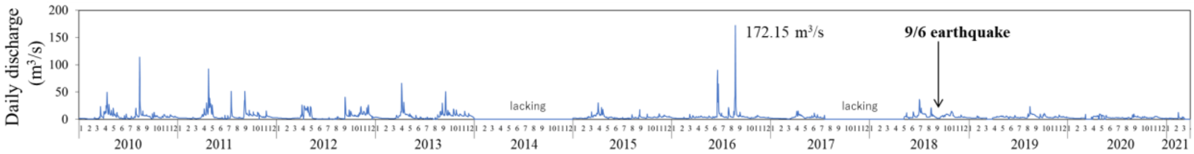

Figure 3. Time series of daily discharge rate (Azuma Bridge gauging station, 2010/1/1 ~ 2021/3/31)

2.3 Physical parameters

Figure 3 shows the daily flow observed at the Azuma Bridge gauging station from 2010 to 2020. The Azuma River has not experienced any major floods since 2016 when it experienced a 172.15 m^3/s outflow (Figure 3). The average daily flow rate from December to April, corresponding to the shishamo spawning and egg production period, was 4.44 m^3/s, with a maximum of 92.51 m^3/s and a minimum of 0.72 m^3/s. The highest snowmelt runoff in the 11 years was in early spring 2013, and relatively low in recent years (data for early spring 2017 are lacking).

Figure 4 shows the average grain size, maximum grain size, and percentages of silt and clay, in the longitudinal direction. The average and maximum grain sizes changed around 5.5 km from the river mouth, regardless of before or after the earthquake. (Figure 4-a, 4-b). This is due to the presence of the largest intake weir at this location (Figure 2). The silt and clay content ratio were found to be significantly high on the right bank of the intake weir and the left bank near 11.0km from the river mouth after the earthquake (Figure 4). However, by two years after the earthquake (November 2020), the situation had almost returned to the pre-earthquake level. The reason for this may be that the Azuma River has not experienced significant floods due to rainfall since the earthquake. The amount of fine-grained sediment runoff from the surface landslides following rainfall is considered relatively small compared to the total area of surface landslides, suggesting that the deposited fine-grained sediment just after the earthquake was washed away within the two years. The percentage of coarse sediment (0.425 to 2.00 mm) as shown in Figure 5, associated with the shishamo spawning sites [3][4][5], did not show showed a clear trend before and after the earthquake.

2.4 Shishamo spawning trend

Figure 6 shows the average density of spawned eggs from 1994 to 2020. These values were converted per m^2 from the results obtained from the quantitative quadrat samplings. The results showed that egg density decreased in 2019 after the earthquake and was lowest in 2020. However, the number of spawned egg densities varied widely from year to year, and it was difficult to judge the impact of the earthquake on spawning. Therefore, as a next step, we compared the annual changes in both the spawning environment and location.

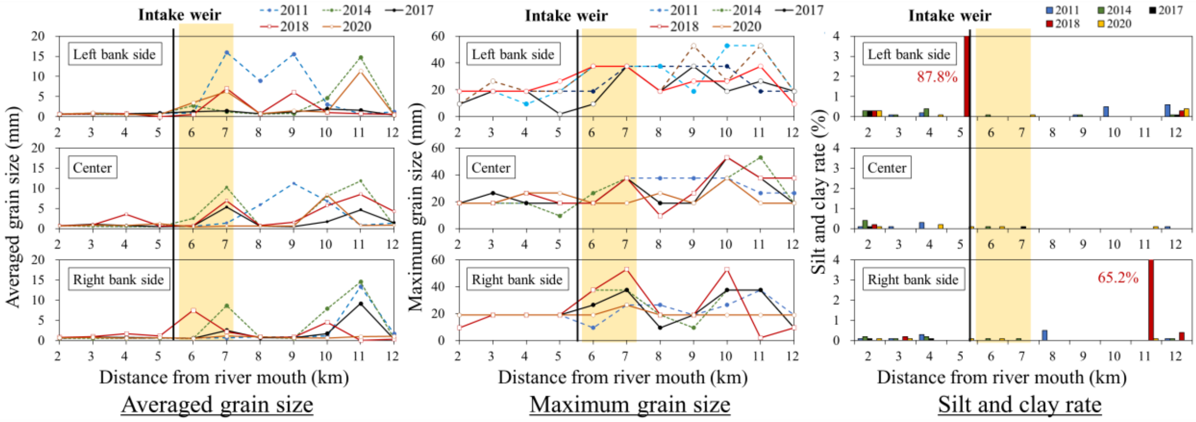

Figure 4. Average grain size, maximum grain size, and percentages of silt and clay, in the longitudinal direction

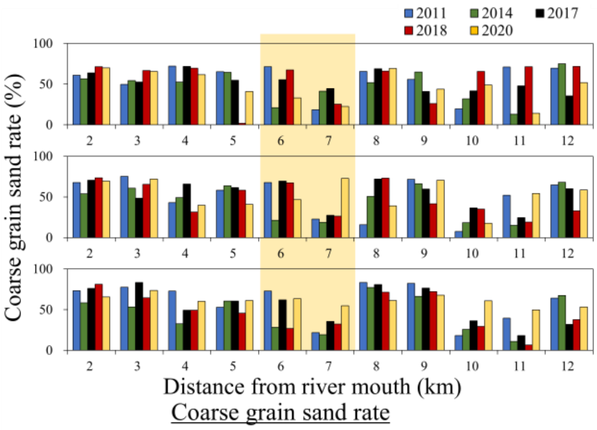

Figure 5. Time series changes of the coarse sediment rate

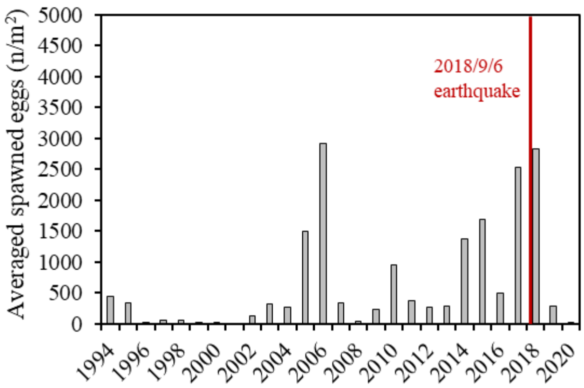

Figure 6. Total number of annually averaged density of spawned eggs from 1994 to 2020

To understand the general shishamo spawning environment in the Azuma River, we compared the relationships of water depth, bottom velocity, and coarse sediment rate to the areas with the highest number of spawned egg densities as illustrated in Figure 7. For these comparisons, data from a series of surveys were used only for the period between 2011 and 2018, when spawning densities were high. According to the figures, the areas with the highest number of spawned eggs tend to be around 0.3 to 0.7 m in depth, around 0.2 to 0.5 m/s in bottom velocity, and with a coarse sediment ratio of 40% or higher.

The rate of shishamo spawning in the longitudinal location from 2010 to 2020 is indicated in Figure 8. The spawning rate R_j is calculated from the following equation:

$$R_j = \frac{p_j}{\sum_{j=1}^{k} p_j} \tag{1}$$

where P_j is the number of spawned egg density (n/m^2) in each survey cross-section, j is the cross-section number, and k is the total cross section numbers.

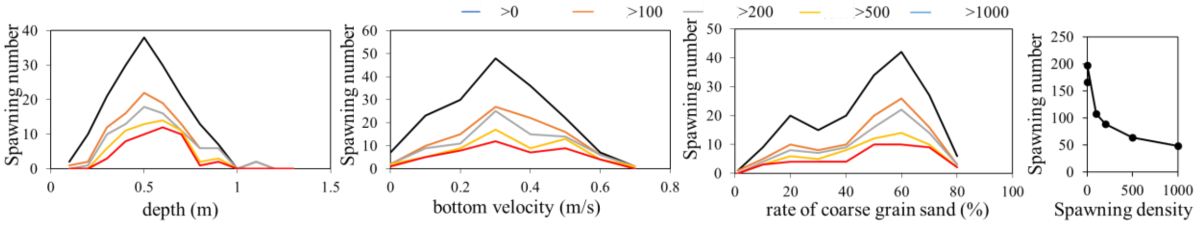

Figure 7. Relationships of water depth, bottom velocity, and coarse sediment rate to the spawning densities

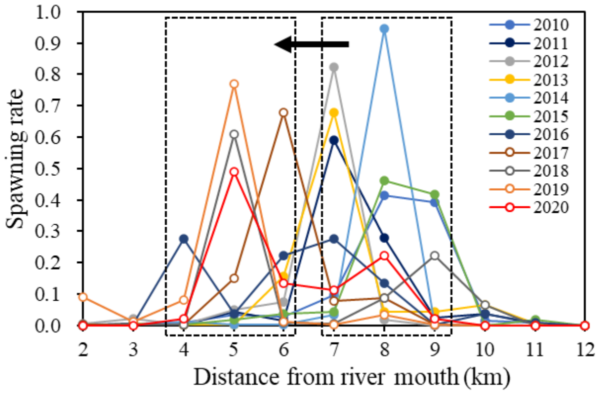

Figure 8. Rate of shishamo spawning in the longitudinal location from 2010 to 2020

Results showed that the location of the main shishamo spawning areas has changed since 2017. The location with the highest number of eggs was upstream from 7.0 km from 2010 to 2016, but has been changed to around 5.0 km to 6.5 km

3 NUMERICAL ANALYSIS

3.1 Unsteady two-dimensional model

Unsteady two-dimensional flow and morphological analysis were conducted to investigate both the suitable spawning sites for shishamo and the transport and deposition characteristics of fine-grained sediment (d_{50} = 0.05 mm) in the lower reaches of the Azuma River, under different discharge scales. The analytical model used iRIC Nays2DH (https://i-ric.org/en/), an open-source free software, that incorporates the concept of the bed-load layer model [5][6][7]to represent morphodynamics under the high concentration and non-equilibrium of sediment transport rate conditions. Details of the model can be found in the manual (https://i-ric.org/en/solvers/nays2dh/ and previous reports [8][9], but changes are described below.

Figure 9 shows an overview of the bedload layer model [5][6]. A bed load layer is provided above the riverbed surface to replicate non-equilibrium sediment transport. When the bed layer has enough amount of sediment required for equilibrium sediment transport rate, the thickness of bedload layer h_b is equal to the thickness of equilibrium bedload layer h_s. In this case, sediment transport rate from the riverbed is given for the equilibriuim. On the other hand, if the bed layer does not have enough sediment volume necessary to transport the equilibrium sediment transport rate, the thickness h_b of the swept sand layer becomes thinner ($h_b < h_s$).

In this paper, only the suspended sand is considered non-equilibrium associated with landslides. When the ratio r_b of the thickness of bedload layer h_b to the thickness of equilibrium bedload layer h_s is less than 1.0, an upward flux of suspended load from riverbed q_{su}, calculated from the Lane-Kalinske Suspended Sediment Equation, is reduced as $q_{su}r_b$ as illustrated in Figure 9.

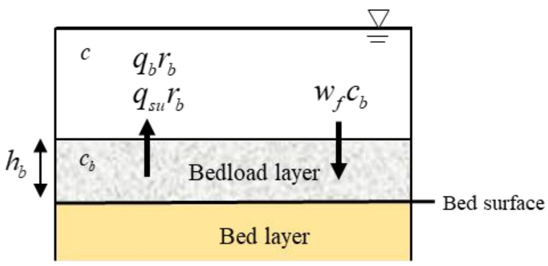

Figure 9. Outline of bedload layer model [5][6], q_b is bed load transport rate, q_{su} is upwind suspended load, w_f is settling velocity of suspended sediment, c is depth-averaged suspended load concentration and c_b is reference concentration of suspended load, h_b is bed load layer thickness.

The governing model of the thickness of the equilibrium bed load layer h_s is modified in Nays2DH as follows in Eq. (2), as proposed by Harada and Egashira [10],

$$\frac{h_s}{h} = \frac{i_e}{(\sigma/\rho - 1)c_b \tan\phi} \tag{2}$$

where h_s is the thickness of equilibrium bedload layer thickness, h is the water depth, σ is the density of sediment density, ρ is the density of water, c_b is the averaged suspended sediment concentration in the bedload layer ($\fallingdotseq$ 0.26), ϕ is the angle of repose, and i_e is the energy gradient, τ_b is the shear stress near the riverbed and g is the gravitational acceleration.

The thickness of bed load layer h_b is calculated from the following Eq.(3),

$$\begin{aligned} h_b &= h_s & ; E_{sd} \geq h_s \frac{c_b}{1-\lambda} \\ h_b &= E_{sd}\frac{1-\lambda}{c_b} & ; E_{sd} < h_s \frac{c_b}{1-\lambda} \end{aligned} \tag{3}$$

where E_{sd} is the thickness of the bed layer and λ is the porosity of the bed layer.

In addition, suspended load concentration given from the upstream boundary of the computational grids was modified to use the observed value in the field instead of the equilibrium concentration.

3.2 Calculation conditions

The computational area was 2.5 to 10.0 km from the river mouth of the Azuma River. The calculation grid size was approximately 5 m in the streamline direction and 2 m in the cross-sectional direction. Initial riverbed material was given as uniform sediment with an averaged grain size of d_m = 5 mm from the field survey data (Hokkaido Governmental survey), and Manning's roughness coefficient was set to 0.03. Initial bathymetry data were created using the 2019 transect survey results (200 m intervals, Hokkaido Governmental survey).

In the calculation, first, flow and morphodynamics were calculated considering only bed load material under several different discharges to compare the spatial distribution of water depth and bottom velocity. Calculations were performed in 6 cases with different flow rates (3, 5, 8, 10, 20, and 30 m^3/s). The average flow rate of the shishamo spawning season is 5.0 m^3/s.

Second, to determine the location where fine sediment is most likely to be deposited, two-dimensional flow and morphodynamics analyses were conducted. In this case, to make the results easier to understand, the riverbed was assumed to be a fixed bed, and the suspended load concentration was only given from the upstream boundary of the computational grids (bed load material is not considered). The hydrograph was reduced from 55 to 5 m^3/s over a 10-hour duration. Calculations were performed in two cases considering the intake weir (open or close) at 5.5 km from the river mouth. Under the weir closure conditions, the riverbed height, located intake weir, was raised by 1.0 m as the height of the weir.

4 RESULTS AND DISCUSSION OF NUMERICAL ANALYSIS

4.1 Variation of suitable spawning areas according to different discharge magnitude

Figure 10 shows the spatial distribution of water depth and bottom velocity in 6 cases with different flow rates. The depth contour map shows that the areas that are too shallow (< 0.3 m/s) for shishamo spawning grounds are relatively few, except the near area of the intake weir (5.5 km).

On the other hand, the situation of bottom velocities is different. The planar distribution of suitable spawning bottom velocities (0.25 ~ 0.6 m/s) changes significantly around 5 m^3/s, the average daily discharge during winter. When the flow rate is 5 m^3/s or less, there are few suitable places for spawning, and it is concentrated near the intake weir around 5.0 to 6.5 km from the river mouth. When the flow rate is about 8 to 10 m^3/s, the suitable spawning area in the low-flow channel moves upstream from 6.5 km, and the range becomes wider. As the flow rate increases further, at the discharge of 20 m^3/s, the bottom velocity exceeds 0.6 m/s in most areas (except for KP 7.0~KP 7.5), and there is concern that the shishamo eggs may become detached from the riverbed material. When the flow rate reaches 30 m^3/s, the near-surface velocity exceeds 0.6 m/s in almost all areas. These results indicate that the suitable spawning area increases when the discharge is higher than the average flow rate. This also means that there are few places for spawning sites when the flow rate is average or lower in early winter, and that spawned eggs flashed away when the snowmelt flood in early spring is too large. However, in the case of the Azuma River, it is considered that there are more restrictions on the spawning potential due to the low flow rate, suggesting ensuring as much flow as possible in the early winter periods.

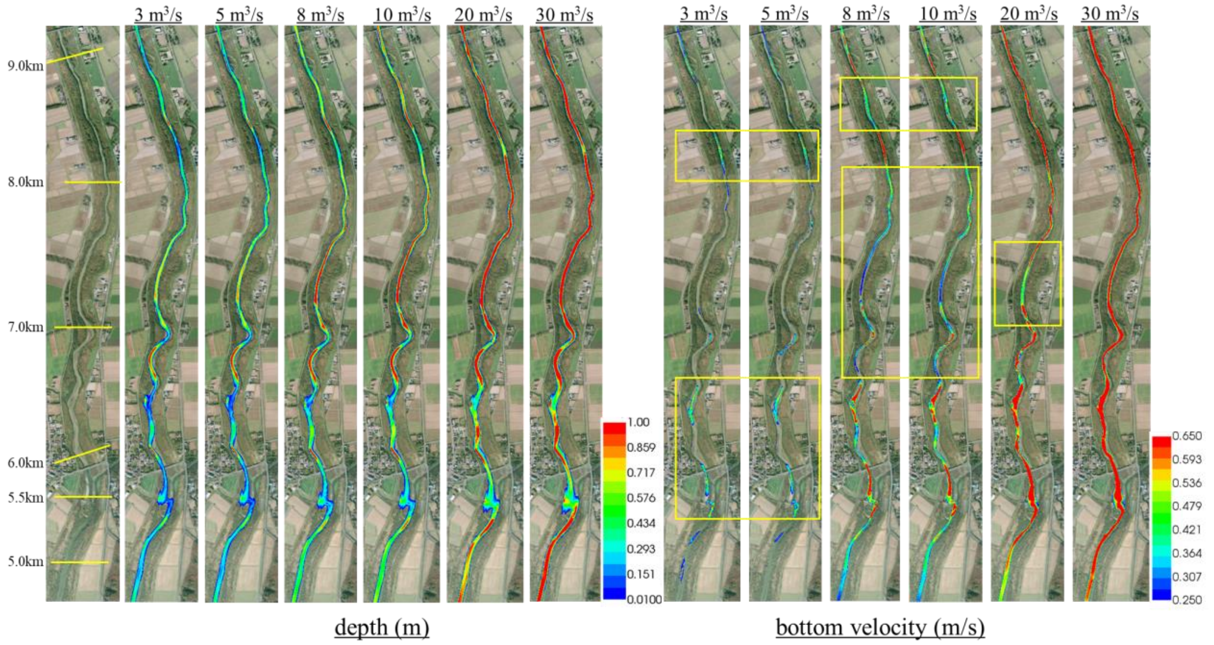

Figure 10. Contour map of depth and bottom velocity in 6 cases

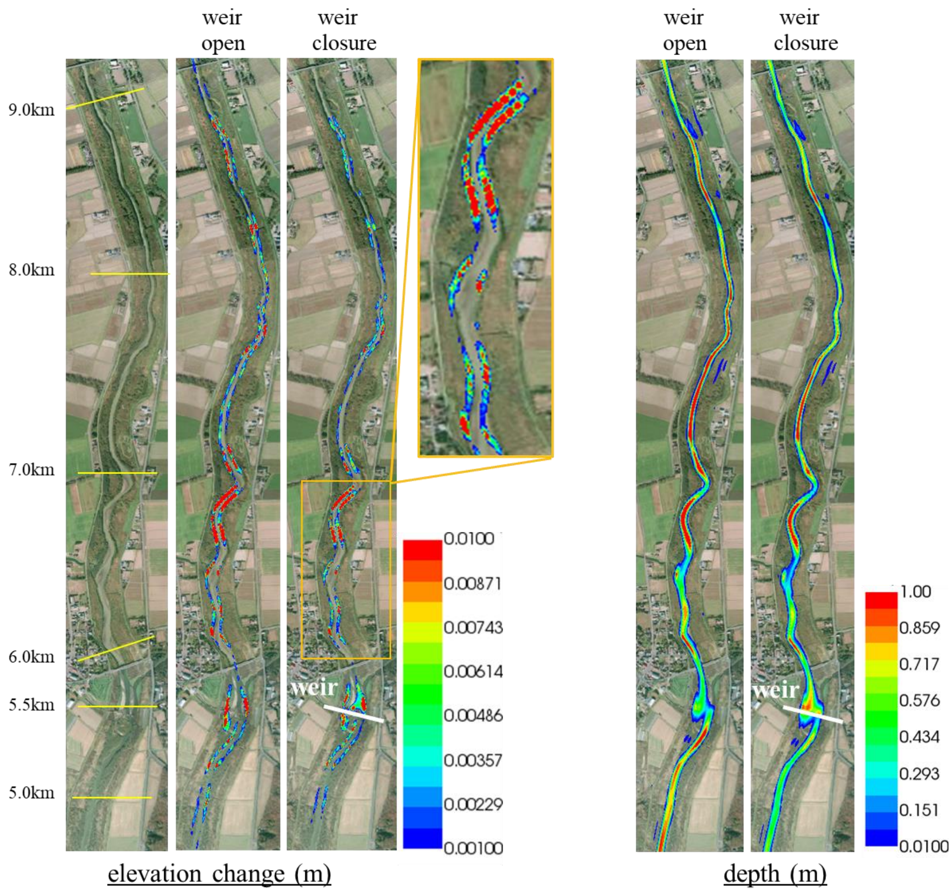

Figure 11. Contour map of bed elevation changes due to suspended load (fine-grain sediment) and depth in 2 cases with open and closure weir.

Figure 11 shows the planar distribution of fine-grained sediment deposits at the end of the calculation, taking into account the opening and closing intake weir at 5.5 km. Results show that fine-grain sediments deposit mainly along riverbanks and less frequently in low-flow channels. The effect of the weir rise on the deposition of fine-grain sediments is likely to be limited to just above the weir. Under the current conditions of this numerical analysis, the influence of fine-grain sediment on the shishamo spawning sites in the Azuma River is estimated to be relatively small. However, sedimentation trends in meandering areas of 6.5-7.0 km are more obvious than in other areas and may result in sedimentation on the sandbars during high water events. Although not considered in this study, it is necessary to keep in mind the long-term effects on a future riverbed and channel morphodynamics because of the accumulation of fine-grain sediment on sandbars, which are usually terrestrial areas.

5 CONCLUSIONS

On September 6, 2018, a magnitude 6.7 earthquake occurred in the eastern part of the Hokkaido Iburi Region, causing more than 6,000 surface landslides in the Azuma River basin. Hence, there are concerns about the impact of fine sediment runoff from landslides and sedimentation in the lower reaches of the Azuma river on shishamo spawning sites. The results of our research were mainly as below:

(1) Field data showed that the most common spawning sites for shishamo are located at depths of 0.3 to 0.7 m and bottom velocities of 0.2 to 0.5 m/s, where the proportion of coarse sediment is high.

(2) The numerical analysis explained that suitable spawning sites are widespread when the flow rate is higher than the average discharge of 5.0 m^3/s in the winter month, suggesting ensuring as much flow as possible in the early winter periods.

(3) The fine-grained sediments that increased after the earthquake were mainly deposited near the riverbanks, and less frequently in low-flow river channels. Under the current conditions of this numerical analysis, the influence of fine-grain sediment on the shishamo spawning sites in the Azuma River is estimated to be relatively small.

6 ACKNOWLEDGMENTS, APPENDICES, AND REFERENCES

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