THE EFFECT OF ALLUVIAL THICKNESS ON HYPORHEIC FLOW QUALITY FROM THE POINT OF CHUM SALMON SPAWNING ENVIRONMENT

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To understand the influence of decreasing gravel thickness on hyporheic flow quality from the viewpoint of chum salmon spawning environment, field surveys and numerical calculations were conducted in 2 sections with different characteristics; one covered with a thin layer of gravel (section of a thin gravel layer) and the other covered with a thick layer of gravel (section of a thick gravel layer) in upper reaches of Ishikari river, Hokkaido Japan. Cross sectional profile, hyporheic flow velocity, dissolved oxygen and inter-gravel temperature were surveyed along the bar front, longitudinally every 50m in these sections. Spawning redds distribution was also surveyed. And numerical calculation of hyporheic flow was conducted. The results show that, in the section of a thick gravel layer, the mean values of hyporheic flow velocity and temperature were high, dissolved oxygen was relatively low and many spawning redds were confirmed. Numerical calculation results show hyporheic flows, including short and long flow paths, were upwelling. On the other hand, in the section of a thin gravel layer, temperature of hyporheic flow was low and few spawning redds were confirmed. Numerical calculation results show that hyporheic flow paths were short. These results indicate that the thick gravel layer condition contributes to spawning environment by supplying hyporheic flows which contains enough dissolved oxygen with warm temperature.

1 INTRODUCTION

Chum salmon spawns on river beds where water upwells from the hyporheic zone and the temperature of river water is relatively high [1]. Additionally, supplying dissolved oxygen to eggs is important for spawning environment [2]. The temperature of hyporheic flow and the dissolved oxygen content in these flows are the important factors for chum salmon spawning environment, and these factors are affected by the hyporheic water residence time [3]. Around bar fronts, the water surface elevation changes suddenly and locally, and this water surface elevation difference generates hyporheic water flowing from the bar crest to the front [4]. The hyporheic water residence time is influenced by the thickness of the gravel layer between the river bed surface and an impermeable layer such as bedrock [5]. Commonly, the thickness of the gravel layer can be reduced due to riverbed degradation in the upstream and midstream river reaches. It is likely that the hyporheic flow quality changes in these places may affect the spawning environment in some way. This study was conducted to understand how differences in the thickness of the gravel layer affect the hyporheic flows and the spawning environment with a view to contributing to the conservation and creation of desirable spawning environment in rivers.

2 METHOD

2.1 Study section

Field surveys were conducted in two sections in the upper reaches of the Ishikari River, Hokkaido, Japan (Figure 1a). These two sections are different in the thickness of the gravel layer. One of these sections is located between KP163.5 and KP164.1, where KP indicates the distance from the river mouth in kilometers. In this section, the

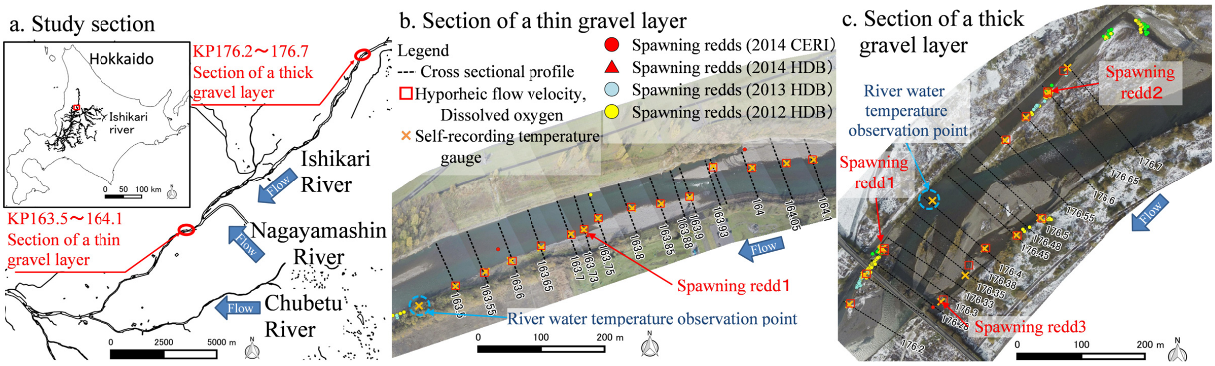

Figure 1. (a) Study section in Ishikari river, Hokkaido, Japan. Survey points and spawning redds distribution in (b) the section of a thin gravel layer and (c) the section of a thick gravel layer, respectively.

elevation of the deepest riverbed surface measured by cross-sectional surveying (described below) is lower than the elevation of the upper surface of the bedrock layer measured by a previous geological survey [6]. In other words, the bedrock layer in this section was eroded and is now covered with a thin layer of gravel. This section is referred to as a section of a thin gravel layer. In addition, the bedrock consists of soft rock (in this case sandstone). The elevation of the deepest riverbed on the upstream edge and the downstream edge of this section is EL122.1 m and EL120.4 m respectively. At the same locations, the elevation of the bedrock surface layer is EL122.37 m and 121.39 m respectively [6], where EL indicates the elevation from mean sea water level of Tokyo Bay. The other section is located between KP176.2 and 176.7. In this section, the thickness of the gravel layer is at least 20 m according to a geological survey conducted before [7]. This section is referred to as a section of a thick gravel layer below.

2.2 Field surveys

Field surveys were conducted at the locations shown in Figures 1b and 1c. These surveys include cross-sectional surveying, surveys of hyporheic flow velocities and dissolved oxygen in hyporheic flows, and measurement of water temperatures by using self-recording gauges. The photos used in Figures 1b and 1c were taken just before this surveying.

For the purpose of understanding the cross-sectional profile of the riverbed, cross-sectional profiles were surveyed by RTK-GPS in a period from November through December, 2014. The measurements were taken at intervals of 50 m along the longitudinal profile of the river, and also at the locations with topographic changes, such as alternate bar locations exchange from side to side.

Hyporheic flow velocities were measured longitudinally at intervals of 50 m along the bar front. Hyporheic flow velocities were surveyed on November 2014 by using the method of Baxter et al. [8]. Specifically, falling head tests were conducted and the total head was measured with a piezometer at points 20 cm deep from the riverbed surface for obtaining permeability coefficients and hydraulic gradients in the vertical direction. Hyporheic flow velocity was calculated as a product of a hydraulic gradient and a permeability coefficient. Positive values and negative values of the hyporheic flow velocity are correlated with upwelling flows and downwelling flows respectively.

At the locations used for surveying hyporheic flow velocities, dissolved oxygen content in hyporheic flows was surveyed on November 2014. In the survey, interstitial water was collected at points 20 cm deep from the riverbed surface by using a hand pump, and an iodine titration method (JIS K0102) was used for analyzing collected water. River water was also collected at the same locations and analyzed by the same method.

With the aim of understanding the water temperature and its changes beneath the riverbed, self-recording gauges (i.e., Tidbit v2 water temperature data loggers of Onset Computer Corporation; ±0.21 °C accuracy) were set at locations used for the hyporheic flow velocity survey on November 2014. In setting the gauge under the riverbed, an open-ended steel pipe was embedded into the riverbed, the gage was dropped through the pipe to the depth of 20 cm from the riverbed surface, and the pipe was pulled out. The gauges were dug out on February 2015, before snowmelt flooding took place. In order to measure river water temperatures, an iron pile was embedded into the riverbed at one location in each section for placing a self-recording gauge at a depth where river water would not be frozen. Measurement data were recorded at hourly intervals. The water temperatures recorded from December 1, 2014 through February 24, 2015 were used for calculating a mean value at each location (i.e., a mean water temperature during the survey period) for the purpose of understanding the characteristics of each location. All the self-recording gauges used for measurement were recovered, but data were missing at some locations in the section of a thin gravel layer. Data were collected at 71.4% of the locations used for measurement.

With a view to understanding the distribution of redds in the two river sections, locations of redds were surveyed. In those sections, the survey was conducted 8 times from October to December. GPSMAP 60CSx (Garmin Ltd.) was used for obtaining coordinates of redds. At selected redds (i.e., one redd in the section of a thin gravel layer (Figure 1b), and three redds in the section of a thick gravel layer (Figure 1c)), hyporheic flow velocities and dissolved oxygen in hyporheic flows were surveyed, and hyporheic water temperatures were measured by using self-recording gauges. Additionally, the results of previous surveys on redds distribution, which were conducted by the Hokkaido Regional Development Bureau from 2011 through 2014, were summarized for determining the quality of the spawning environment in each section.

2.3 Analyses

2.3.1 Flow regime calculation

Flow regime was calculated with the aim of understanding the planar distribution of the river water levels that were to be used for the calculation of hyporheic flows. The flow regime calculation was performed by using Nays2DH, an analytical solver in iRIC software [9]. In creating computational grids, the topography data obtained by cross-sectional surveying were applied to the low-water channel of the river, and Fundamental Geospatial Data (Digital Elevation Model: 5-meter elevation grids) created by the Geospatial Information Authority of Japan [10] were applied to the high-water channel. The width of the high-water channel was set at 100 m, almost the same width as the high-water channel in the study sections. The flow rate was assumed to be 40 m^3/s, a mean value of the 185-day flow rates from 2007 through 2012 observed at Nagayama and Pippu Discharge Gauging Stations in the vicinity of the locations for surveying in this study. A 185-day flow rate is a rate of discharge which is ensured on 185 days a year, and it is 43.9 m^3/s at Nagayama and 37.5 m^3/s at Pippu.

2.3.2 Hyporheic flow calculation

Hyporheic flows were calculated by using DTRANSU-3D･EL [11], a 3-D computational model. The plane grids used for the flow regime calculation were expanded toward the depth direction for conversion into finite element grids compatible with DTRANSU-3D･EL. As shown in Table 1, the computational grids were extended to the depth of 10 m from the riverbed surface in the section of a thin gravel layer. The depth was set at 10 m because the gravel layer on the riverbed was 1m thick in this section, and also because it was unlikely that the bedrock (having a low permeability coefficient) would significantly affects the distribution of hyporheic flows. In the section of a thick gravel layer, the computational grids were extended to the depth of 20 m from the riverbed surface because a geological survey [7] had confirmed that the gravel layer thickness was at least 20 m in this section.

Conditions used for calculating hyporheic flows are shown in Table 1. For the permeability coefficients of the gravel layers, the mean values obtained as a result of falling head tests conducted in each section was used. The effective porosity of the gravel layer 0.25 [12] was used for the gravel layer of each section. For the section of a thin gravel layer, the properties of the bedrock underlying the gravel layer were set as follows. Usually, field tests need to be performed to obtain an accurate value of the permeability coefficient regarding the rock. For the sake of simplicity, an intermediate value of the sandstone permeability coefficients reported in multiple studies [13] is used in this paper. These coefficients differ by several orders of magnitude, and their intermediate value is 3.4×10^{-7}m/s (≒0.03 m/day). The effective porosity of the sandstone layer was set at 0.0925 [12].

In the section of a thin gravel layer, the elevation of the deepest riverbed surface surveyed in this study was lower than the bedrock elevation reported in other studies [6]. Thus, for the purpose of the hyporheic flow calculation, the elevation of the bedrock surface in the low-water channel in the section of a thin gravel layer was calculated by using a proportional distribution method on the basis of the deepest riverbed elevations on the upstream and downstream edges of the same section.

The river water level obtained in the flow regime calculation described above was used as the total head that affects the grid points on the upper surface of the riverbed. According to a survey [7] that was conducted in the section of a thick gravel layer, the groundwater level at a location 100 m from the top of the slope along the low-

Table 1. Calculation conditions of hyporheic flow.

items		Calculation condition	
Calculation area	Section	KP163.50～164.10	KP176.20～176.70
	lateral direction	approximately 100m from lower channel	
	vertical direction	10m deep from bed surface	20m deep from bed surface
Grid size（X×Y×Z)		approximately 4×4×0.3m(0.5m)	approximately 4×4×0.4m(0.5m)
Hydroulic conductivity of gravel layer		63.1m/day	90.5m/day
Hydroulic conductivity of bedrock (sandstone)		0.03m/day	-
Effective porosity of gravel layer		0.25	
Effective porosity of bedrock (sandstone)		0.0925	
Total head on end of lateral side		river water level + 1m	

※values in parenthesis indicate vertical grid size on higher water channel

water channel is higher than the river water level by about 1m. Thus, the groundwater level 1m higher than the river water level was given as a boundary condition of the right and left banks. In order to mitigate possible impacts of the boundary conditions given to the upstream and downstream edges on the hyporheic flow calculation, a 100 m-long section having the same cross-sectional shape as the upstream edge or the downstream edge of the low-water channel in the computational grids was added to either end of the low-water channel. It was assumed that the rate of flow running into and out of the upstream and downstream edges in each section was equal to a product of a mean value of the bed slope and a mean value of the permeability coefficient. The hyporheic flow calculation results were visualized in the form of 3D streamlines by using Paraview [14].

3 RESULTS

3.1 The quality of hyporheic flows and the number of redds

Mean water temperatures during the survey period were calculated on the basis of the data collected by self-recording gauges. These values, and mean and standard deviation values of the hyporheic flow velocity as well as of the dissolved oxygen content are shown in Figure 2 for the two sections and also for the redds in these sections. In the section of a thick gravel layer, the mean hyporheic flow velocity was 32.3 m/day and 51.5 m/day at locations with upwelling flows and downwelling flows, respectively. These values are larger than the corresponding mean values in the section of a thin gravel layer, 4.9 m/day and 5.7 m/day. In the section of a thick gravel layer, the mean dissolved oxygen content in hyporheic flows was 9.3 mg/l, which was slightly lower than the corresponding value in the section of a thin gravel layer, 11.1mg/l. The mean water temperature of a thick gravel layer during the survey period was 2.3 ℃, higher than the corresponding value in the section of a thin gravel layer, 0.6 ℃. The mean hyporheic flow velocity regarding all redds where hyporheic water was upwelling was 75.5 m/day, which was higher than the mean hyporheic flow velocity in the two sections. The mean water temperature during the survey period at these redds was 2.2 ℃, being as high as the mean water temperature in the section of a thick gravel layer.

The locations of redds confirmed in the surveys from 2011 through 2014 are shown in Figures 1b and 1c. Additionally, the number of redds surveyed by the Hokkaido Regional Development Bureau is shown in Figure 3 for each section. In the section of a thin gravel layer, very few redds were confirmed while many redds were located in the section of a thick gravel layer except in 2014.

3.2 Characteristics of the hyporheic flow quality at various locations

Figure 4 shows the hyporheic flow velocity and the mean water temperature during the survey period at each location surveyed, shown in Figure 1b and 1c in the two sections. The dissolved oxygen content in hyporheic flows and river water at the same locations are shown in Figure 5.

In the section of a thin gravel layer, the hyporheic flow velocity, the dissolved oxygen content, and the mean water temperature do not vary greatly among the locations surveyed (Figures 4a and 5a).

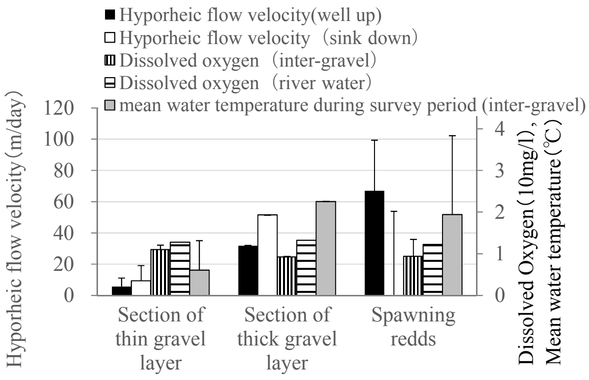

Figure 2. Hyporheic flow quality by sections and redds.

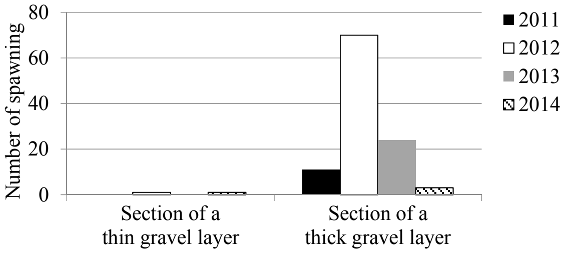

Figure 3. Number of redds by sections

a. Section of a thin gravel layer

b. Section of a thick gravel layer

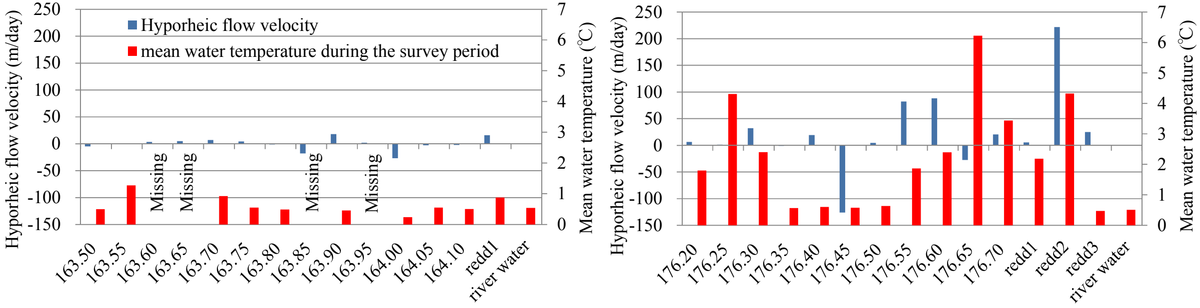

Figure 4. Hyporheic flow velocity and mean water temperature during the survey period.

a. Section of a thin gravel layer

b. Section of a thick gravel layer

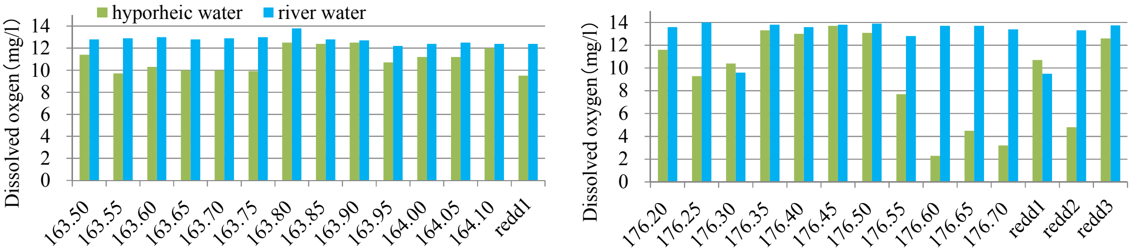

Figure 5. Dissolved oxygen by sections.

In the section of a thick gravel layer, the mean water temperature at KP176.25, 176.65, 176.7 and redd 2 was much higher at 4.3°C, 6.2°C, 3.4°C, and 4.3°C respectively in comparison with the mean water temperature of the section, 2.3°C (Figures 4b). In the same section, the dissolved oxygen content at KP176.6, 176.65, 176.7 and redd 2 was 2.3 mg/l, 4.5 mg/l, 3.2 mg/l, and 4.8 mg/l (Figure 5b), less than half the value of the dissolved oxygen content confirmed at all other locations, around 10 mg/l. Thus, various values of hyporheic flow velocity, hyporheic flow temperature and dissolved oxygen exists in the section of a thick gravel layer.

3.3 Distributions of streamlines obtained as a result of hyporheic flow calculation

Figure 6 shows the distributions of streamlines obtained by calculating hyporheic flows in each of the two sections. In both sections, groundwater flows into the river transversely from the high-water channels on the right and left side. While vertical hyporheic flows are confirmed in the section of a thick gravel layer, very few are confirmed in the section of a thin gravel layer. Regarding the section of a thick gravel layer, the streamlines in Figure 6b shows that groundwater flowing from the high-water channels on the right and left side penetrate the riverbed and upwells from the riverbed near the bank of the low-water channels. At KP176.45 -176.65 on the right side of the low-water channel, there are two kind of hyporheic flow upwelling; both long seepage paths of groundwater from the area around the river and short seepage paths of hyporheic water due to the terrain specific to bars.

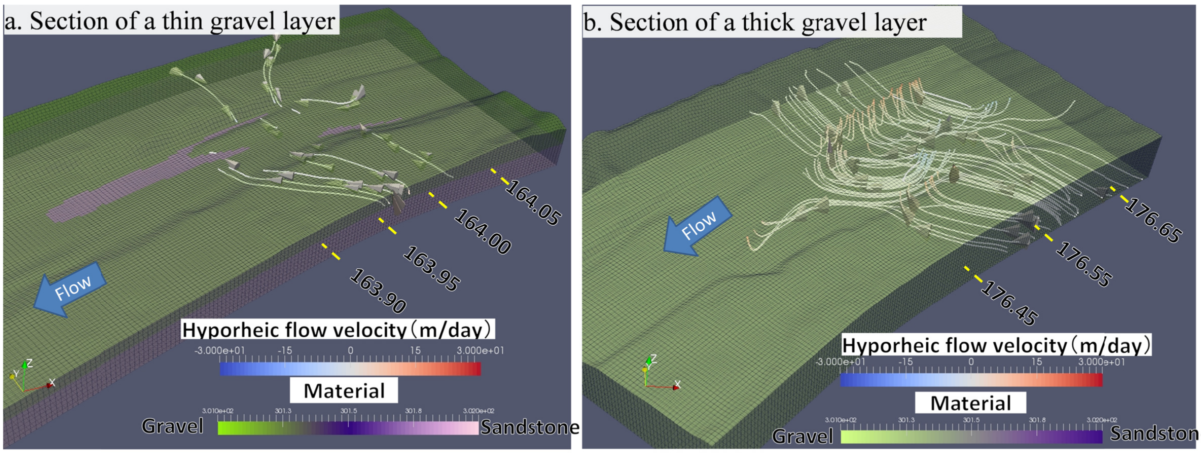

Figure 6. Calculation results of hyporheic flow path by sections.

4 DISCUSSION

4.1 Difference in the hyporheic flow quality due to the thickness of gravel layers

In the section of a thick gravel layer, the hyporheic flow velocity and the water temperature were higher and the dissolved oxygen content was slightly lower in comparison with the section of a thin gravel layer (Figure 2). The dissolved oxygen in hyporheic flows is consumed during flowing inter-gravel because of the metabolic activity of interstitial communities. Thus, dissolved oxygen is consumed with increase of hyporheic flow residence time [3]. Accordingly, it is possible that hyporheic flows having a long duration of residence time occurred in the section of a thick gravel layer. In addition, saturated-dissolved oxygen content decreases when the water temperature increases, but this fact alone cannot explain the reason why the dissolved oxygen content in the hyporheic flows was lower in the section of a thick gravel layer. Although the water temperatures during water sampling were not measured, on the assumption that the water temperatures were between 4°C and 8°C, the saturated-dissolved oxygen content is 13.1-11.8mg/l [12]. At KP176.60, 176.65, 176.32, and Redd 2, the dissolved oxygen content in the hyporheic flows was particularly low at 2.3 mg/l, 4.5 mg/l, 3.2 mg/l, and 4.8 mg/l, and these values are less than half the values of saturated-dissolved oxygen content (Figure 5b). It is difficult to conclude that the temperature of the river water increased to cause a significant reduction in the dissolved oxygen content in the hyporheic flows. From the viewpoint of the characteristics of the water temperature, hyporheic flows having a long duration of residence are likely to upwell in the section of a thick gravel layer. Hyporheic water that has traveled along long seepage paths is colder in summer and warmer in winter than river water [3]. Thus, it is possible that hyporheic water having a long duration of residence was upwelling at the locations where the dissolved oxygen content was significantly low or the mean water temperature was relatively high in the section of a thick gravel layer (Figures 4, 5).

Hyporheic flows having a long duration of residence were in the section of a thick gravel layer probably because of the thickness and the continuousness of the gravel layer. Based on numerical calculations, Tonina [5] indicated that a gravel layer having a thickness of 0.3 times as large as the bar wavelength was necessary to ensure that an impermeable layer at the bottom of the gravel layer would not reduce the residence time of the hyporheic flows specific to the riverbed with alternate bars. In the section of a thick gravel layer, alternate bars were not clearly formed, thus it couldn't be assumed that the gravel layer had a thickness of 0.3 times as large as the bar wavelength. However, a geological survey [7] shows that the gravel layer is at least 20 m thick. Therefore, it is likely that the impact of an impermeable layer on hyporheic flows specific to the riverbed with bars was very small. Additionally, when the gravel layer is thick and continuous, hyporheic flows having a long duration of residence run into the river from the upper reaches and around the river. When a geological survey was conducted in the section of a thick gravel layer, it was confirmed that the groundwater level in the flood channel 100 m away from the bank of the low-water channel was 1m higher than the river water level [7]. This suggests that groundwater flowed into the river in this section as indicated by numerical calculation results.

The result of hyporheic flow calculations showed that groundwater from around the river was upwelling at KP176.45-KP176.65 on the riverbed near the right bank, and that hyporheic water that was specific to the riverbed with bars, and which traveled short seepage paths, was also upwelling at the same locations (Figure 6b).

This result suggests that hyporheic water that has traveled multiple lengths of seepage paths upwells on the riverbed near the river banks when the gravel layer is thick enough, the groundwater level around the river is higher than the river water level, and a bar front formed near the river banks.

In the section of a thin gravel layer, the elevation of the deepest riverbed was lower than the elevation of the upper surface of the soft rock layer that was measured by a geological survey conducted in the past [6], and thus the gravel layer is likely to be very thin. The result of field surveys showed that the hyporheic flow velocity and the mean water temperature were low and the dissolved oxygen content was high in this section. Accordingly, it is probable that the volume of the hyporheic water that traveled long seepage paths, as well as of the hyporheic flow velocity was small. The result of hyporheic flow calculations also indicates the same probability (Figure 6a). As Tonina & Buffington [3] suggested, the thin gravel layer is correlated with a relatively short residence time of the hyporheic flows that are specific to the riverbed with bars. Additionally, it is possible that the thin gravel layer helps prevent the inflow of hyporheic water that has a long duration of residence and flows from the upper reaches and around the river.

4.2 Thickness of a gravel layer assessed from the viewpoint of spawning environment

For chum salmon eggs to hatch, a cumulative water temperature of 480°C･day is necessary. For salmon fry to rise to the surface, a cumulative water temperature of 960°C･day is needed [16]. At least 5 mg/l of dissolved oxygen is required for ensuring sound growth of salmon fry [17]. Malcolm *et al.* [2] reported that the dissolved oxygen content was low at locations that were strongly affected by groundwater. These locations were correlated with a high mortality rate of salmon fry. As mentioned above, the dissolved oxygen content is higher when hyporheic water has a shorter duration of residence. On the other hand, the temperature of hyporheic flows is lower when the flows have a shorter duration of residence in winter. For maintaining a favorable spawning environment, it is desirable that both the dissolved oxygen content and the water temperature are high. To meet this condition, it is necessary that hyporheic flows having a short duration of residence coexist with hyporheic flows having a long duration of residence. From the viewpoint of the need for hyporheic water which has traveled seepage paths of multiple lengths, Baxter & Hauer [18] suggested that a favorable spawning environment of bull trout (*Salvelinus confluentus*) required local land features, such as riffles and pools, as well as a long section of a river where the valley width was partially large. In this study, it was not confirmed whether a cumulative water temperature necessary for eggs to hatch was secured because self-recording gauges were recovered before snowmelt flooding began. In the section of a thick gravel layer, the mean water temperature in a period from December 1, 2014 through February 24, 2015, when the water temperature was relatively low in winter, was higher than 3.5°C at some locations (Figure 4b). Regarding these locations, the cumulative water temperature would be 525°C (i.e., 3.5°C x 30 days × 5 months (Nov-Mar). Thus, it is likely that a temperature higher than 480°C, a cumulative temperature necessary for eggs to hatch, was secured at these locations. In the section of a thick gravel layer, the required dissolved oxygen content of 5 mg/l was maintained in general, although the dissolved oxygen content was as low as 2.3 and 3.2 mg/l at some survey points. Few redds were confirmed in the section of a thin gravel layer, while many were confirmed in the section of a thick layer though the number of redds varied from year to year. Thus, the section of a thick gravel layer was better than the other section as a spawning ground of chum salmon because hyporheic flows having a short duration of residence coexisted with hyporheic flows having a long duration of residence, and also because the dissolved oxygen content and the water temperature were more favorable for spawning.

5 CONCLUSION

Field surveys and numerical calculations were conducted for analyzing how the differences in the thickness of a gravel layer would affect hyporheic flows and the spawning environment of chum salmon. And we concluded that, from the viewpoint of the dissolved oxygen content and the water temperature, the conditions suitable for spawning are ensured when there are a continuous thick gravel layer and bars. Because hyporheic flows having various durations of residence wells up in such characteristic section.

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